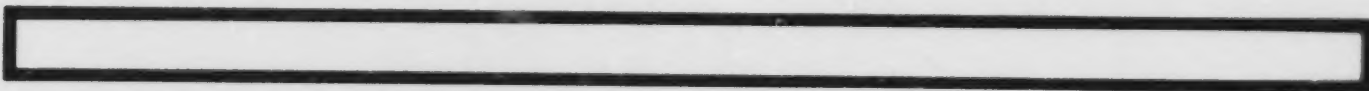


PB86-154176

Design Scale-Up Suitability for
Air-Stripping Columns

(U.S.) Environmental Protection Agency
Cincinnati, OH

Jan 86



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January 1986

DESIGN SCALE-UP SUITABILITY FOR AIR-STRIPPING COLUMNS

by

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Cooperative Agreement No. CR-810247-01

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This study was conducted in cooperation with
The Village of Brewster, New York

WATER ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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Air-stripping in a packed column is sometimes used to remove volatile organic compounds from contaminated water supplies. Since the design engineer frequently uses data from a pilot air-stripping column to design a full-scale system, the suitability of such design scale-up was investigated. A total of 48 experimental runs was made in packed columns of four different diameters (6, 12, 24 & 57 in.) at air-to-water ratios ranging from 5:1 to 50:1. Water from the Village of Brewster, NY, well fields (contaminated with PCE, TCE and cis-1,2 dichloroethylene) was used. Various packing types (1/2, 1 & 3 in. saddles, 2 in. TRI-PACKS) were used in the experimental runs. Generally, it was found that the mass transfer coefficient increased with column diameter, i.e., mass transfer coefficients obtained from a pilot column tend to be conservative. Thus, a full-scale column designed from pilot data would tend to be oversized. The experimental mass transfer coefficients were compared with values calculated from the Onda mass transfer coefficient model. Based on these results, it appears that the Onda model would tend to give a conservative design for a full-scale system. Using a cost model developed by USEPA/ODW/TSD, the 2 in. TRI-PACKS (of the packings tested) gave the most cost-effective design for a full-scale system. No operational problems were encountered during freezing weather other than rupture of some sample lines.		
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FOREWORD

The U. S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

Contamination of groundwater supplies with volatile halogenated organic solvents has occurred at a number of places in the United States. A cost-effective method for removing such contaminants consists of air-stripping in a counter-current packed column, and engineering design guidelines are needed to design these large-scale packed columns. The principal objective of this project is to investigate and confirm the scale-up capability of an air-stripping packed column from pilot to full-scale module.

Francis T. Mayo, Director
Water Engineering Research
Laboratory

ABSTRACT

An investigation was conducted to determine the suitability of design scale-up from pilot-scale to full-scale air-stripping columns used in the removal of volatile organic compounds from contaminated water supplies.

Forty eight experimental runs were made in packed columns of four different diameters (6, 12, 24, and 57 inches) at air-to-water ratios ranging from 5:1 to 50:1. The study used water from the Village of Brewster, New York, well fields (contaminated with tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene). Various packing types (1/2-inch saddles, 1-inch saddles, 3-inch saddles, and 2-inch TRI-PACKS) were used in the experimental runs.

Generally, the mass transfer coefficients increased with column diameter--that is, mass transfer coefficients obtained from a pilot column tend to be conservative. Thus, a full-scale column designed from pilot data would tend to be oversized. This was true even when the pilot column had a column diameter to packing size ratio of 12:1 or 24:1.

The experimental mass transfer coefficients were compared with values calculated from the Onda mass transfer coefficient model. Generally, the two values were in reasonably good agreement. Based on these results, it appears that the Onda model tends to give a conservative design for a full-scale system. Using a cost model developed by the U. S. Environmental Protection Agency, the 2-inch plastic TRI-PACKS (of the packing types tested) resulted in the most cost-effective design for a full-scale system. No operational problems were encountered during subfreezing weather other than rupture of some sample lines.

This report was submitted in fulfillment of Cooperative Agreement No. CR-810247-01 by Nathan L. Jacobson & Associates, under the sponsorship of the U. S. Environmental Protection Agency and the Village of Brewster, New York. This report covers a period from September 1, 1982 to November 30, 1985, and the experimental work was completed as of May 1985.

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METRIC CONVERSIONS

MULTIPLY	BY	TO OBTAIN
inches	0.0254	meters
feet	0.3048	meters
gal/min (gpm)	3.785×10^{-3}	cu meters per min
gal/min per ft ²	4.07×10^{-2}	cu meters per min per sq meter
cu ft per min (cfm)	2.83×10^{-2}	cu meters per min
cfm per ft ²	0.305	cu meters per min per sq meter

ACKNOWLEDGMENT

We wish to acknowledge the considerable assistance and/or constructive suggestions provided by the following personnel:

Nathan L. Jacobson, Thomas J. Kalinowsky, and Bernard F. Baker of Nathan L. Jacobson & Associates;

Michael D. Cummins, J. Keith Carswell, and Dr. O. Thomas Love of the United States Environmental Protection Agency; and

Mayor E. Stannard Tuttle, Jr., Lou Gaspirini, and Carl Peaters of the Village of Brewster, New York.

SECTION 1

INTRODUCTION

BACKGROUND

The Village of Brewster in New York State has a serious groundwater contamination problem--namely, their well fields are badly contaminated with industrial chlorinated solvents (tetrachloroethylene, trichloroethylene, cis-1,2 dichloroethylene, and vinyl chloride). A continuing program has been under way to evaluate various approaches of providing a potable water supply, such as decontamination of water from the existing well fields by air-stripping or location of a new water supply source. Air-stripping was selected as the most cost-effective approach.

In 1982, a packed column pilot plant (12-inch diameter with 18 feet of 1-inch packing) was erected at the Village well fields, and an air-stripping test program was conducted. This pilot column was designed for 99% removal of tetrachloroethylene at the average annual temperature at Brewster, using a design procedure described in the technical literature (1 and 2) and augmented by the U. S. Environmental Protection Agency's Technical Support Division (EPA-TSD). Test results were very encouraging: The removal of tetrachloroethylene exceeded 99% (with 1-inch ceramic saddles at an air:water ratio of 20:1).

EPA-TSD, which had developed a computer program based on theory similar to that noted above, undertook a cooperative study with this pilot plant, and the data were analyzed using their program. More recently, EPA-TSD tested a larger packed column pilot plant (2-foot diameter with 2-inch plastic saddles) at the Village well fields.

Based on the various studies conducted by the Village's consulting engineer, a decision was made to design and construct a full-scale air-stripping column for the Village's water supply. Since three different sizes of air-stripping columns would now be available (two pilot and one full-scale column), a proposal for a cooperative research agreement was made to EPA's Drinking Water Research Division (EPA-DWRD) to conduct tests in these columns with various packing materials. At the request of EPA-DWRD, a fourth column diameter (6-inch) was added.

OBJECTIVES OF THIS PROJECT

The principal objective of this cooperative research agreement is to investigate and confirm scale-up capability of an air-stripping packed column from a pilot-scale to a full-scale module (design capacity of 0.5 MGD). Secondary objectives are as follows:

1. Develop engineering design guidelines by evaluating mass transfer coefficients and Henry's coefficients in full-scale and pilot-scale packed columns,
2. Evaluate the effect of cold weather operation on the full-scale module (i.e., the effect of sub-freezing air temperatures on operability and the effect of low water temperatures on Henry's coefficient),
3. Evaluate the limiting column diameter:packing size ratios for pilot columns (i.e., are ratios of less than 12:1 feasible?),
4. Evaluate by means of a computer program the economics of different packing sizes and operating conditions, i.e., the optimum range for air:water ratio and air pressure drop to give minimum life cycle cost), and
5. Document the installed equipment cost of the air-stripping technique in a full-scale module.

Some additional secondary objectives were initially proposed but were deleted from the project because of a budget shortfall. (The shortfall occurred when construction bids were received and found to be significantly higher than the engineering estimate.) The deleted objectives were to:

1. Evaluate the potential effect(s) of air-borne contaminants, bacteria, and inorganics on the quality of the water as a drinking water supply,
2. Evaluate alternative methods of preventing and/or removing iron deposits from the column packing, and
3. Operate the full-scale column in a routine fashion for 10 months and document the operating and maintenance costs.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Based on the results reported here, the following conclusions and recommendations were reached:

1. Generally, the mass transfer coefficients increased as the column diameter increased (i.e., the mass transfer coefficients increased as the column diameter to packing size ratio increased). There did not appear to be any cut-off point--that is, the trend continued beyond the column diameter to packing size ratios of 12:1. This trend is attributed to a so-called wall effect that would be more pronounced in a smaller-diameter column.
2. Because of the trend noted above, it appears that using pilot plant data to design a full-scale column will result in a conservative design.
3. Based on the cost model described here, the 2-inch TRI-PACKS of the packings tested gave the most cost effective design for a full-scale system (i.e., it gave the lowest production cost per million gallons of water).
4. Reasonably good agreement was obtained between the experimentally derived mass transfer coefficients and those calculated from the Onda model. Based on these results, it appears that the Onda correlation tends to give a conservative design for a full-scale system.
5. The 57-inch diameter column was run continuously through periods of subfreezing weather, and the low air temperatures did not interfere with the operation of the packed column. The only problem encountered with low temperatures was with the copper tubing sample lines; some of these lines split open during the night-time (even though the sample valves were left partly open). For any future designs, it is recommended that any such sample lines be insulated to prevent freezing in the line.

SECTION 3

DESCRIPTION OF EQUIPMENT

GENERAL ARRANGEMENT

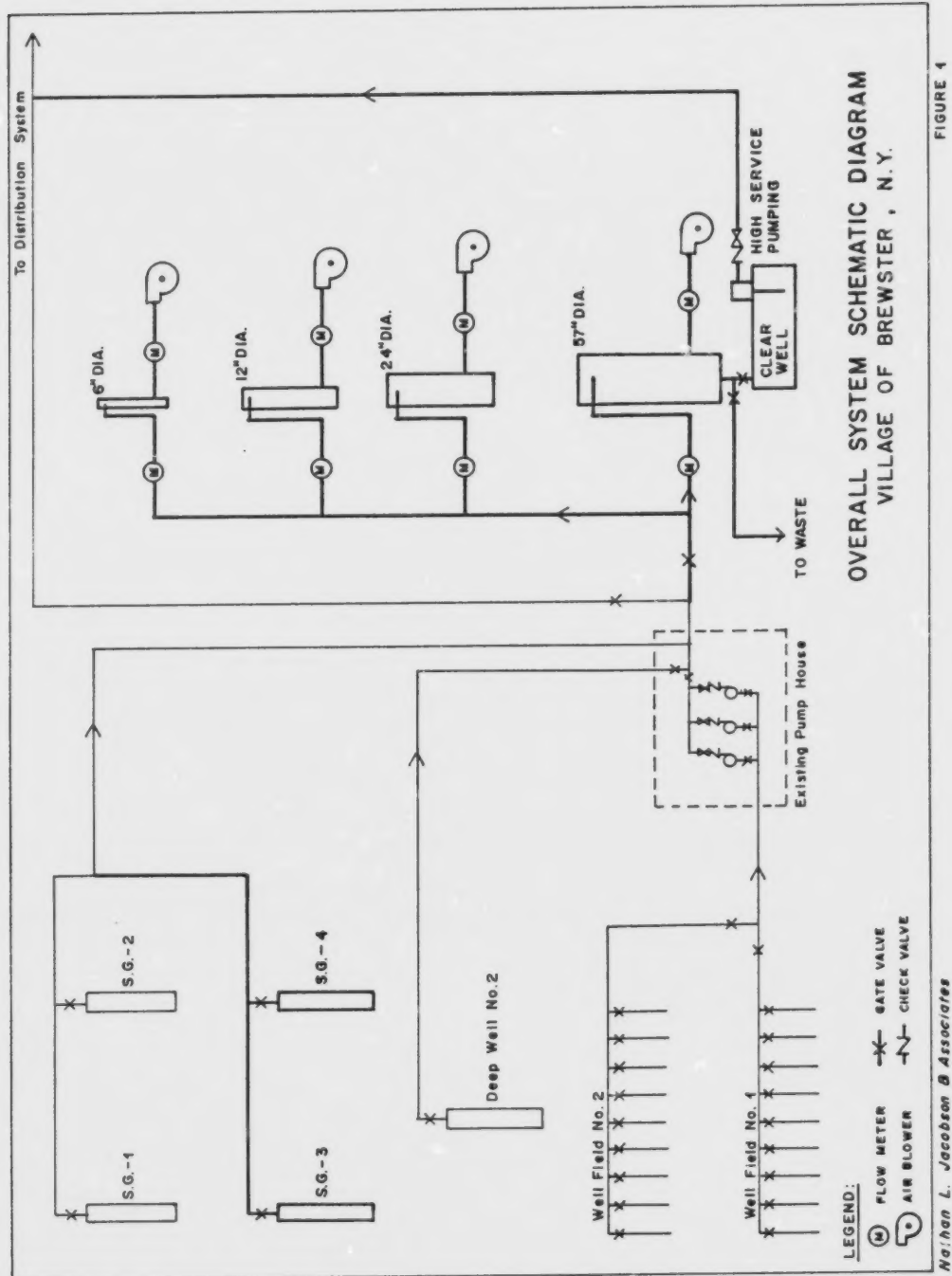
An overall system schematic diagram is shown in Figure 1. Water can be supplied from two old well fields (Well Fields 1 and 2), two old gravel pack wells (SG 1 and 2), two new gravel pack wells (SG 3 and 4), and/or a rock well (Deep Well 2). All of these Village wells are contaminated with the synthetic chlorinated organics to some degree, with Well Field 1 having the highest contamination levels.

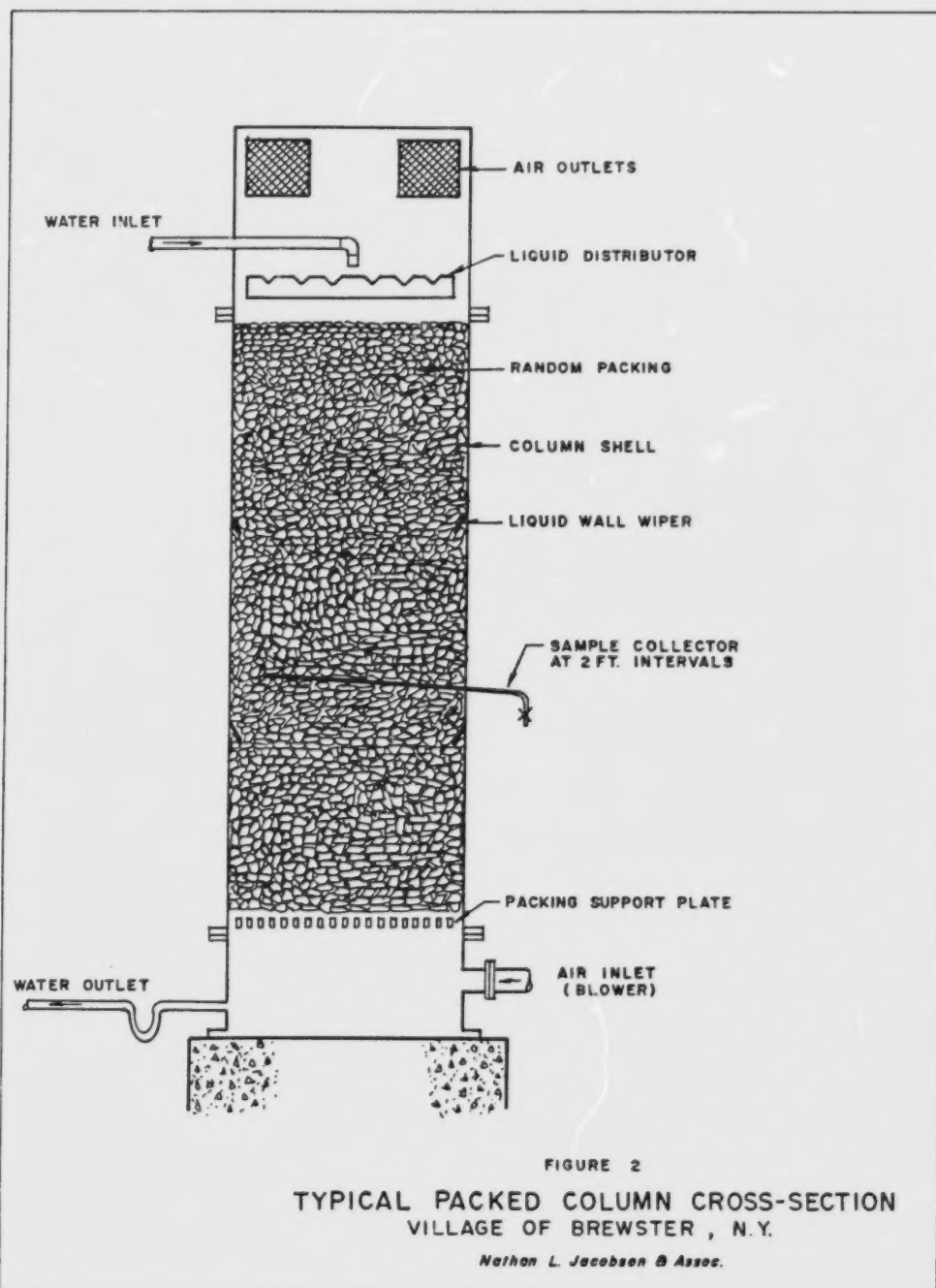
There are three pilot-size columns and one full-scale air-stripping column. Three of the columns (6-inch, 12-inch, and 57-inch diameters) are hard-piped installations; the EPA-TSD column (24-inch diameter) was set-up on a temporary basis for its scheduled tests. Details on column construction are provided below. A sketch showing the construction (typical) of an air-stripping packed column is presented in Figure 2.

SIX-INCH DIAMETER PILOT COLUMN

A photo showing the installed 6-inch column (along side of the 57-inch column) is shown in Figure 3. The column is constructed of aluminum, with five flanged sections. The three middle sections, each 6 feet long, contain the packing (18-foot packing height). The liquid distributor (mounted at the top of the column) is a perforated basket type. There are two wall collectors located at 6-foot intervals within the packing. These collectors are shaped like partial funnels (4-1/4-inch inside diameter) and are designed to remove excess water from the walls of the column and redistribute the liquid onto the packing. The packing support plate has a corrugated shape with openings in the corrugations that exceed 100% of the column cross-sectional area.

There are seven sample taps spaced at equal intervals within the packing; each sample tap extends into the packing and is constructed of copper tubing with the top half removed. Two additional sample taps are provided for the water into and out of the column.





An air blower forces ambient air into the bottom of the column (below the packing support plate). The air flow is measured with a rotameter, and the water flow is measured with a water meter and stop watch.

TWELVE-INCH DIAMETER COLUMN

A photo showing the installed 12-inch column is shown in Figure 4. The column is constructed of fiberglass, with five flanged sections. The three middle sections, each 6 feet long, contain the packing (18-foot packing height). Design of the liquid distributor, two wall collectors (9-1/2-inch inside diameter), and packing support plate are similar to the 6-inch column.

There are seven sample taps spaced at equal intervals within the packing; the sample tap design (half tube) is similar to the 6-inch column. Again, there are two additional sample taps for the water into and out of the column.

A blower forces ambient air into the bottom of the column, and the air flow is measured with an Annubar* sensing element and a combination included-vertical manometer. The water flow is measured with a water meter and stop watch.

TWENTY-FOUR INCH DIAMETER COLUMN

A photo showing the temporary installation of the 24-inch column is presented in Figure 5. The column is constructed of aluminum with seven sections flanged together, plus a bottom section separated by an air gap. There are six sections, each 3 feet long, that contain the packing (18-foot packing height). The liquid distributor at the top of the column consists of a pipe manifold with four overflow ports located in a square pattern. There are five wall collectors located at 3-foot intervals within the packing; these collectors are similar to the funnel-shaped collectors described previously except that the discharge (inside) edge is fluted and the liquid runs off of spike-like arms into the packing. Packing support plates (flat grates with rectangular openings) are located at the bottom of each of the column sections.

There are nine sample taps spaced at equal intervals within the packing. These sample taps are half tubes that extend 18 inches into the packing, with the central 12 inches being open and the 6 inches closest to the wall being closed. There is also an inlet water sample tap; the outlet water can be sampled at the open discharge of the column.

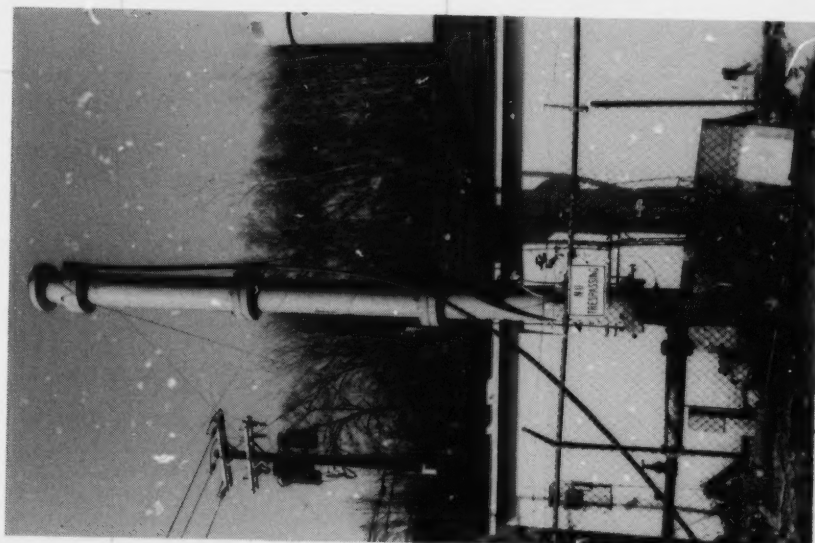
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Figure 4. Twelve-Inch Diameter Column

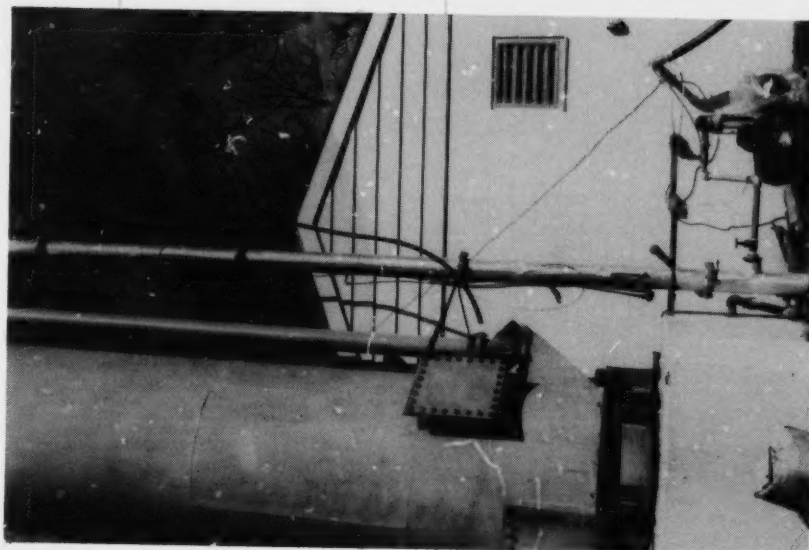


Figure 3. Six-Inch Diameter
Column (alongside of 57-inch column)

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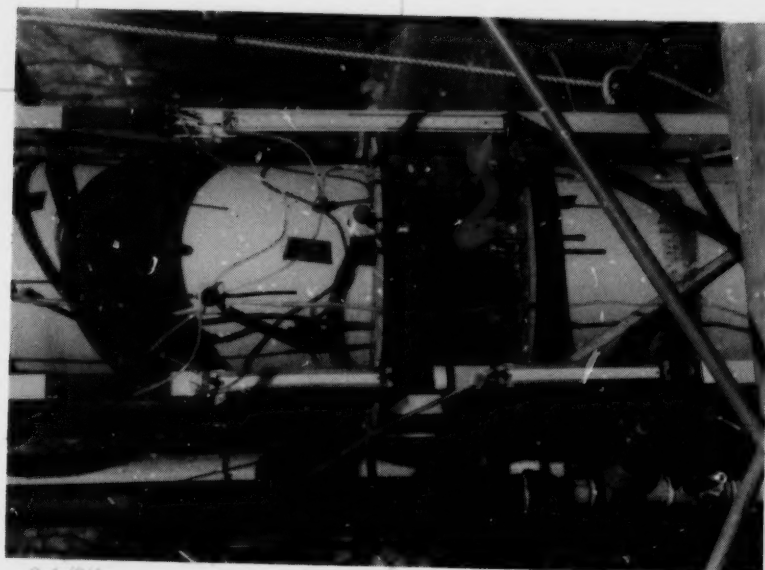


Figure 6. Bottom of 24-Inch Diameter Column

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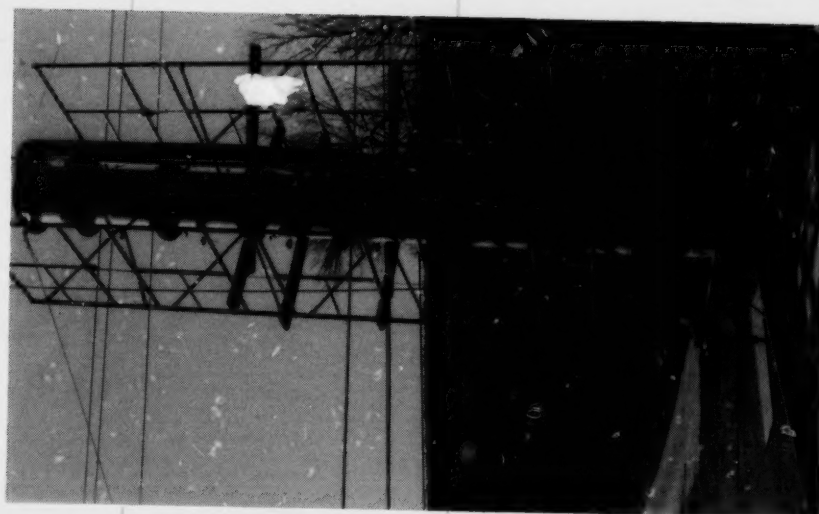


Figure 5. Twenty-Four Inch Diameter Column

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The 24-inch column uses a suction blower (from the top of the column) for air flow, hence there is an open section at the bottom of the column to allow ambient air to enter (see Figure 6). The airflow is measured with an orifice plate and an inclined-vertical manometer. The water flow is measured with an orifice plate and a mercury manometer. A complete description of the 24-inch column is presented in Appendix A.

FULL-SCALE COLUMN

A photograph of the 57-inch diameter column, as installed, is shown in Figure 7. This full-scale column has a nominal capacity of 0.5 MGD and was designed for 99% removal of tetrachlorethylene at an air to water ratio of 33:1 (with 1-inch plastic saddles at a height of 17 feet 9 inches).

The column is constructed of aluminum with the main section fabricated in one piece (there is one flange only for the top section). The liquid distributor consists of two rectangular-shaped parting boxes that drain into three rectangular-shaped weir boxes (mounted at right angles to the parting boxes). Overflow from the six edges of the three weir boxes provides liquid distribution across the top of the packing. (Actual packing depth in this column is 17 feet-9 inches). There are three wall collectors equally spaced within the packing bed; these collectors are shaped as an inverted "L" and have an inside diameter of 51-inches. The packing support plate has corrugations similar in design to the 12-inch column.

There are seven sample taps, spaced at equal intervals, within the packing. Each sample is collected in a 1-inch aluminum angle (open "V" facing up) that runs across the full diameter of the column to within 1/2-inch of the opposite wall. The aluminum angle slopes slightly towards the sample withdrawal end. Again, there are two additional sample taps for the water into and out of the column.

There are two air blowers, connected in parallel, for forcing ambient air into the bottom of the column; one blower is used for normal operation and the other is on standby (see Figure 8). The air flow is measured with an Annubar sensing element and an inclined-vertical manometer. The water flow to the top of the column is measured with an Annubar sensing element and a direct-reading dial indicator.

PACKING CHARACTERISTICS

The characteristics of the various packing materials tested are presented in Table 1. Included in that table are the names of the vendors and some of the physical properties of each packing, such as surface area and void volume.

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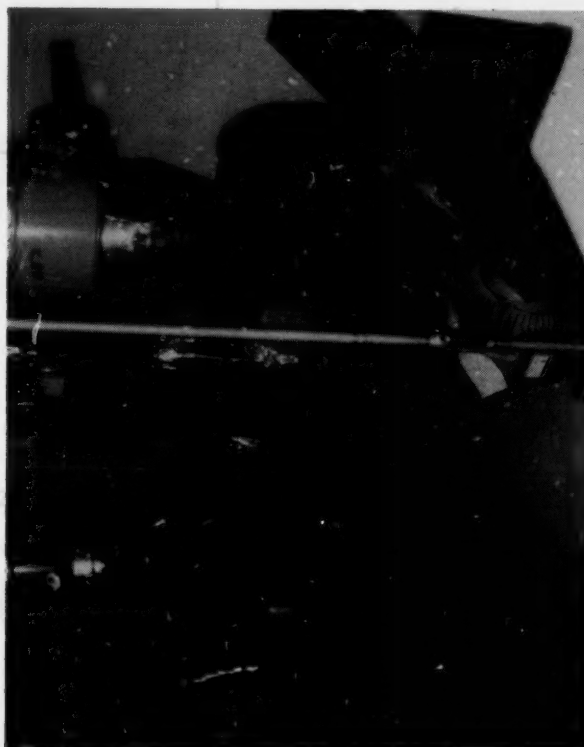


Figure 8. Dual Blowers for 57-Inch Diameter Column

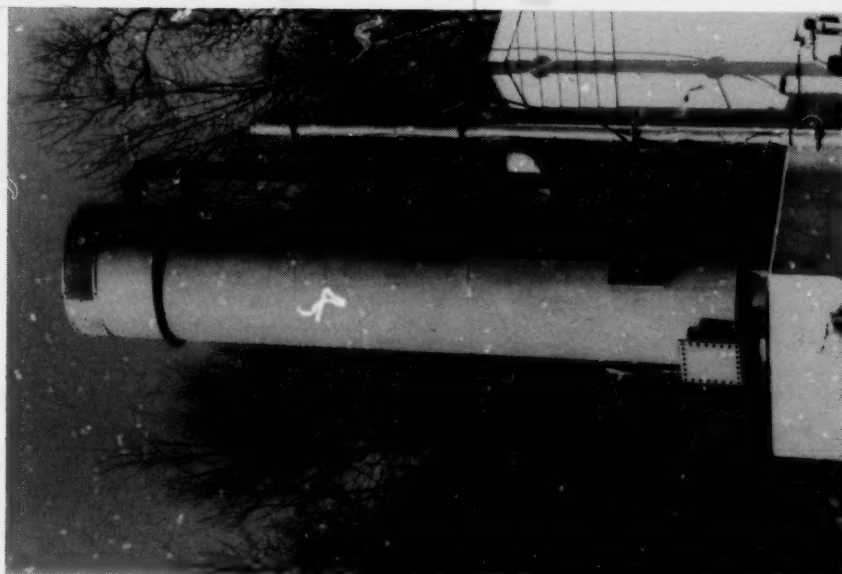


Figure 7. Fifty-Seven Inch Diameter Column (with 6-inch column alongside)

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TABLE 1. PACKING TYPES AND CHARACTERISTICS USED IN TEST PROGRAM

Nominal Size (inches)	Description (Material & Type)	Vendor's Name	Surface Area (sq ft/cu ft)	Free Space (%)	Packing Factor (1/ft)
1/2	Ceramic Saddles (a)	Koch	190	70	200
1	Plastic Saddles (b)	Koch	63	91	30
3	Plastic Saddles	Koch	27	94	15
2	Plastic TRI-PACKS	Jaeger	42	96	15

(a) Critical surface tension for ceramic is 61 dynes/cm.

(b) Critical surface tension for plastic (polypropylene) is 33 dynes/cm.

COST OF FULL-SCALE AIR STRIPPING FACILITY

The actual construction cost of the full-scale column (57-inch diameter) is tabulated in Table 2. These costs include the building (housing the air blowers, pumps, and electrical controls), ancillary equipment, sitework, and contractor's overhead and profit. This air-stripping facility has a design capacity of 347 gpm (0.5 MGD) and a maximum capacity of 600 gpm (0.86 MGD).

AIR DISCHARGE PERMIT

The New York State Department of Environmental Conservation required that a "Process, Exhaust or Ventilation System" permit application be submitted. Based on the anticipated air emissions (99% of the volatile organic compounds in the incoming water), no difficulty was experienced in obtaining the permit.

TABLE 2. CONSTRUCTION COST OF FULL-SCALE AIR-STRIPPING FACILITY

Construction Cost (including Installation)

A.	Process Equipment	
	1. Column shell	)
	2. Column internals	) \$40,775.
	3. 1" plastic saddle packing)	
	4. Air blowers (two)	4,620.
	5. High service pumps (two)	18,980.
	Total Process Equipment (sum of above)	\$64,375.
B.	Air Well (also Building Foundation)	46,818.
C.	Piping, Valves & Appurtenances	25,000.
D.	Air Ductwork and Appurtenances	7,260.
E.	Chemical Feed Equipment	7,000.
F.	Instrumentation	1,320.
G.	Electrical	49,103.
H.	Building Superstructure & Sitework (a)	72,971.
	SUBTOTAL	\$273,847.
I.	Additional support equipment, piping, valves and appurtenances for research operations	9,792.
	Contractor's Overhead and Profit (included in above)	
	TOTAL CONSTRUCTION COST	\$283,639.

(a) Includes sitework, catch basin, masonry, carpentry, metal work, painting, exterior piping and valves, and bonding.

SECTION 4

PLAN OF WORK AND TEST PROCEDURE

OUTLINE OF TEST RUNS

The packing materials tested were 1/2-inch ceramic saddles, 1-inch and 3-inch plastic saddles, and 2-inch plastic TRI-PACKS. The planned experimental conditions were selected to allow evaluation of: (a) different column diameters with the same packing material (at the same air and water velocities), and (b) different column diameter to packing size ratios (i.e., minimum column diameter:packing size ratio).

An outline of the planned test conditions is presented in Table 3. Because of budgetary considerations, the experimental plan had to be limited to fit the available funding level.

TABLE 3. OUTLINE OF EXPERIMENTAL PLAN

	COLUMN DIAMETER			
	6-inch	12-inch	24-inch	57-inch
Packing Types:				
Saddles ^(a)	1/2" & 1"	1" & 3"	1"	1" & 3"
TRI-PACKS	2"	2"	2"	-
Packing Height ^(b)	18"	18"	18"	17'- 9"
Air-To-Water Ratios ^(c)	5:1 10:1 20:1 35:1 50:1	5:1 10:1 20:1 35:1 50:1	5:1 10:1 20:1 35:1 50:1	-(d) 10:1 20:1 35:1 50:1

- (a) Plastic packing materials were used in all cases, except for the 1/2-inch saddles which are not available in plastic at this size; 1/2-inch ceramic saddles were used in this case.
- (b) The full-scale column was designed for a packing height of 17 feet 9 inches.
- (c) Volume:volume basis.
- (d) There was not sufficient well-pumping capacity to plan for the 5:1 ratio in the full-scale column.

PRACTICAL FLOW LIMITATIONS

In the case of some of the test runs, the 5:1 and 10:1 air-to-water ratios could not be run because of water flow limitations (due to either insufficient pumping capacity from the Village's well fields or excessive pressure drop in a column or water feed line). These flow limitations are discussed in Section 5.

FLOW CONDITIONS SELECTED

The air and water flow conditions (velocities) used for the various packing materials are shown in Table 4. These flow conditions were selected by EPA-TSD to give a calculated air pressure drop gradient of 1/16-inch water column per foot of column packing. (Note that the conversion factors for converting the English units to metric units are given on page vi).

TABLE 4. FLOW CONDITIONS FOR PLASTIC AND CERAMIC SADDLES AND TRI-PACKS
FLOW CONDITIONS FOR 1-INCH PLASTIC SADDLES

<u>Air:Water Ratio</u> (volume basis)	<u>Liquid Loading</u> (gpm/ft ²)	<u>Air Loading</u> (scfm/ft ²)
5:1	45	30
10:1	38	50
20:1	24	65
35:1	16	78
50:1	13	87

FLOW CONDITIONS FOR 3 INCH PLASTIC SADDLES AND 2 INCH TRI-PACK

<u>Air:Water Ratio</u>	<u>Liquid Loading</u> (gpm/ft ²)	<u>Air Loading</u> (scfm/ft ²)
5:1	75	50
10:1	58	77
20:1	37	100
35:1	25	120
50:1	20	130

FLOW CONDITIONS FOR 1/2 INCH CERAMIC SADDLES

<u>Air:Water Ratio</u>	<u>Liquid Loading</u> (gpm/ft ²)	<u>Air Loading</u> (scfm/ft ²)
5:1	20.0	13.4
10:1	14.9	20.0
20:1	9.64	25.8
35:1	6.59	30.8
50:1	5.10	34.1

TEST PROCEDURE

The following test (operating) procedure was used for the experimental runs:

1. Set the air flow rate and the water flow rate for the conditions desired for each run. (It was usually necessary to adjust the water flow several times to get the desired rate.)
2. Allow column conditions to stabilize for approximately 20 minutes. During this time, drain and flush the column sample tube risers at least two times.
3. Initiate the run by logging the test conditions.
4. Collect water samples in duplicate (seven to nine sample locations in column plus inlet and outlet) in accordance with EPA standard procedure.
5. Reread the test conditions to confirm that flows have not changed significantly.

Record temperature conditions, blower power measurements, water pH (in and out), and environmental conditions.

For the 24-inch column, the sample tubes are relatively short (approximately 1 foot long), therefore flushing was done only once. Also, for this column, blower power measurements (gasoline-engine driven) were not made.

As much as was possible, the same feed water was used for all the runs. However, it was not possible to maintain a constant contamination level in the feed water for two reasons:

1. The contamination levels in the various wells increased with time over the course of the test period. This was especially true for Well Field 1 and SG 3 & 4.
2. The range of water flows required with the various sized columns was very broad (i.e., from 1.0 gpm to 660 gpm). This required blending water from the various well sources (up to as many as four sources) to meet the higher flow requirements, and each of these sources had a different contamination level.

During an initial project peer review that is routinely conducted for EPA, a question with regard to possible cross-contamination of the influent air between operating columns was raised. To eliminate this possibility, one column was operated at a time (with the air to the other columns shut-off). This eliminated the need for collection and analysis of air samples to evaluate this possible cross-contamination issue.

SAMPLE ANALYSES

All water samples were collected in duplicate with the use of EPA-approved type sample vials and in accordance with EPA procedures. Samples collected from the 12, 24, and 57-inch columns were packed in ice and shipped via overnight freight to Holzmacher, McLendon & Murrell (H2M Corp.). Samples collected from the 6-inch column were mailed to the EPA-DWRD, Cincinnati, Ohio (per the EPA Cooperative Agreement). Samples were analyzed for volatile organic compounds (VOCs) in accordance with EPA Method 601.

QUALITY ASSURANCE

A Quality Assurance Project Plan, required by the Special Conditions of this Cooperative Agreement, was prepared and approved by the appropriate EPA officials before data collection was begun.

SECTION 5

OPERATING CONDITIONS AND EXPERIMENTAL RESULTS

OPERATING CONDITIONS

Forty eight experimental runs were made in the four packed columns with various packings and at various air:water ratios. Tabulations of the experimental conditions are presented in Tables 5 through 8 for the 6-inch, 12-inch, 24-inch, and 57-inch diameter columns, respectively. The run numbers represent the chronological order in which the experimental runs were made. These tables show the water (well) source, the packing type, the water and air flows, the air:water ratio, the column pressure drop (ΔP), the water and air temperatures, and the pH of the water.

For purposes of data evaluation, the runs were assigned an analysis number as shown in Table 9. All runs with the same column and same packing material were collectively referred to as a data group. The run numbers in the last column correspond to the run numbers in Tables 5 through 8. Also shown are the air:water ratio and the air and water flows (loading).

WATER SAMPLE RESULTS

As noted previously, water samples were collected (for each run) at the inlet to the column, at approximately 2 foot intervals within the packing (sample taps A, B, C, etc.), and at the outlet from the column. Approximately 430 water samples were collected and analyzed for these experimental runs.

The results of these water analyses (for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene) are presented in Appendix A, Tables 2, 3, and 4. These same data are plotted as concentration profiles in Appendices B, C, and D for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene, respectively. In the case of vinyl chloride, the concentration levels in the mixed water from the various well sources were too low (usually less than 1 microgram per liter) to provide any meaningful data. However, prior test work with the 12-inch diameter column (using WF-1 only) had shown that vinyl chloride could be readily stripped.

TABLE 5 - TABULATION OF EXPERIMENTAL RUNS - 6-INCH DIAMETER COLUMN

Run No.	Date	Water Source	Packing Type	Water Flow		Air Flow		Air:Water Vol. Ratio	Column AP Inches H ₂ O	Temperatures, °C			Water pH	
				gpm	gpm/ft ²	cfm	cfm/ft ²			Water In	Water Out	Amb. Air In	In	Out
6	11/8/84	WF-1, SG-3/4, DW	1/2" Saddles	3.91	19.9	2.6	13	5:1	0.3	10.5	11.2	14.0	7.1	7.5
7	11/8/84	WF-1, SG-3/4, DW	1/2" Saddles	2.85	14.5	3.9	20	10:1	0.3	10.6	11.4	11.0	6.7	7.5
8	11/8/84	WF-1, SG-3/4, DW	1/2" Saddles	1.94	9.90	5.08	25.9	20:1	0.8	10.6	11.6	9.5	7.3	7.7
9	11/8/84	WF-1, SG-3/4, DW	1/2" Saddles	1.33	6.79	6.07	31.0	34:1	0.4	10.6	11.5	9.2	7.3	7.7
10	11/8/84	WF-1, SG-3/4, DW	1/2" Saddles	1.02	5.20	6.7	34	49:1	0.1	10.6	11.0	8.3	7.3	8.0
12 (a)	12/4/84	WF-1, SG-3/4	1/2" Saddles	3.9	20	2.6	13	5:1	0.2	10.6	10.1	5.4	7.2	7.7
13 (b)	12/4/84	WF-1, SG-3/4	1/2" Saddles	0.98	5.0	6.7	34	51:1	0.9	10.5	9.0	5.2	-	-
18	2/20/85	WF-1, SG-3/4	2" Tri-Packs	4.0	20	25	128	47:1	1.1	10.0	9.5	1.5	7.4	7.8
20	2/20/85	WF-1, SG-3/4	2" Tri-Packs	5.0	26	23.5	120	35:1	1.0	10.2	9.8	5.2	7.0	7.5
22	2/20/85	WF-1, SG-3/4	2" Tri-Packs	7.2	37	19.6	100	20:1	1.0	9.8	9.6	8.5	6.9	7.6
24	2/20/85	WF-1, SG-3/4	2" Tri-Packs	11.3	57.7	15.0	76.5	9.9:1	1.7	10.2	9.7	8.5	7.1	7.9
26	2/20/85	WF-1, SG-3/4	2" Tri-Packs	14.7	75.0	10	51	5.1:1	4.0	10.1	9.5	4.2	7.1	7.4
44	5/13/85	WF-1, SG-3/4	1" Saddles	4.6	23	12.7	64.8	21:1	0.5	11.0	13.2	27.0	7.4	7.8
45	5/13/85	WF-1, SG-3/4	1" Saddles	3.18	16.2	15.5	79.1	36:1	0.6	11.1	13.7	28.5	-	-
46	5/13/85	WF-1, SG-3/4	1" Saddles	2.55	13.0	17.1	87.2	50:1	0.65	11.0	14.2	28.4	7.3	7.9
47	5/14/85	WF-1, SG-3/4	1" Saddles	8.85	45.2	5.85	29.8	4.9:1	0.3	10.2	11.5	21.5	6.5	7.1
48	5/14/85	WF-1, SG-3/4	1" Saddles	7.45	38.0	9.8	50	10:1	0.5	10.2	11.5	20.0	6.6	7.5
(a)	Repeat of Run No. 6.													
(b)	Repeat of Run No. 10.													

TABLE 6 - TABULATION OF EXPERIMENTAL RUNS - 12-INCH DIAMETER COLUMN

Run No.	Date	Water Source	Packing Type	Water Flow		Air Flow		Air:Water Vol. Ratio	Column ΔP Inches H ₂ O	Temperatures, °C		Water pH	
				gpm	gpm/ft ²	cfm	cfm/ft ²			Water In	Water Out	In	Out
2	10/24/84	WF-1, SG-2/3/4, DW	3" Saddles	15.7	20.0	102	130	49:1	0.8	11.1	11.2	6.7	7.6
4	10/24/84	WF-1, SG-2/3/4, DW	3" Saddles	20	26	94	120	35:1	1.1	11.5	11.3	6.7	7.6
5	10/29/84	WF-1, SG-2/3/4	3" Saddles	30.0	38.2	78.5	100	20:1	1.8	11.4	11.8	6.7	7.4
15 (a)	1/3/85	WF-1, SG-3/4	3" Saddles	15.7	20.0	100	127	48:1	1.1	10.0	9.0	-	-
16 (b)	1/9/85	WF-1, SG-3/4	3" Saddles	19.0	24.2	93	118	37:1	1.2	9.0	8.4	-	-
17	2/20/85	WF-1, SG-3/4	2" Tri-Packs	15.0	19.1	102	130	51:1	1.1	10.0	9.8	7.2	7.5
19	2/20/85	WF-1, SG-3/4	2" Tri-Packs	20.3	25.9	93.8	119	35:1	1.2	9.8	9.0	7.1	7.7
21	2/20/85	WF-1, SG-3/4	2" Tri-Packs	30	38	78.5	100	20:1	1.0	10.1	9.6	7.1	7.6
23	2/20/85	WF-1, SG-3/4	2" Tri-Packs	44.8	57.1	60.5	77.1	10:1	1.8	10.2	10.0	7.4	7.6
25	2/20/85	WF-1, SG-3/4	2" Tri-Packs	59.0	75.2	39.3	50.1	5.0:1	7.7	10.1	9.8	7.3	7.6
39	5/13/85	WF-1, SG-3/4	1" Saddles	35.5	45.2	24	30.6	5.1:1	0.4	10.4	11.1	7.6	8.4
40	5/13/85	WF-1, SG-3/4	1" Saddles	29.5	37.6	39.3	50.0	10:1	0.7	10.8	11.2	7.0	7.8
41	5/13/85	WF-1, SG-3/4	1" Saddles	18.5	23.6	51	65	21:1	0.85	11.2	11.6	7.2	8.1
42	5/13/85	WF-1, SG-3/4	1" Saddles	12.6	16.0	61	78	36:1	1.0	11.5	12.4	7.6	8.4
43	5/13/85	WF-1, SG-3/4	1" Saddles	10.2	13.0	68.3	87.0	50:1	1.1	12.2	13.0	7.4	8.5
(a)	Repeat of Run No. 2.												
(b)	Repeat of Run No. 4.												

TABLE 7 - TABULATION OF EXPERIMENTAL RUNS - 24-INCH DIAMETER COLUMN

Run No.	Date	Water Source	Packing Type	Water Flow		Air Flow		Air:Water Vol. Ratio	Column ΔP Inches H ₂ O	Temperatures, °C				Water pH	
				gpm	gpm/ft ²	cfm	cfm/ft ²			Water In	Water Out	Amb. Air In	Water Out	In	Out
27	3/5/85	WF-1, SG-3/4, DW	2" Tri-Packs	180	57.3	240	76.4	10:1	0.9	10.4	9.8	10.8	6.9	6.9	7.5
28	3/5/85	WF-1, SG-3/4, DW	2" Tri-Packs	120	38.2	310	98.7	19:1	0.8	10.8	10.2	12.4	6.8	6.8	7.4
29	3/5/85	WF-1, SG-3/4, DW	2" Tri-Packs	78	25	380	121	36:1	0.8	10.8	10.4	11.6	6.7	6.7	7.4
30	3/5/85	WF-1, SG-3/4, DW	2" Tri-Packs	63	20	410	130	49:1	1.0	10.4	10.2	11.0	6.9	6.9	7.4
31	3/6/85	WF-1, SG-3/4, DW	1" Saddles	140	44.6	94	30	5.0:1	0.5	9.4	10.3	0.0	7.0	7.0	7.7
32	3/6/85	WF-1, SG-3/4, DW	1" Saddles	120	38.2	160	50.9	10:1	0.8	10.0	10.2	0.0	6.8	6.8	7.6
33	3/6/85	WF-1, SG-3/4, DW	1" Saddles	75	24	200	63.7	20:1	1.0	10.0	10.0	1.8	6.8	6.8	7.6
34	3/6/85	WF-1, SG-3/4, DW	1" Saddles	50	16	240	76.4	36:1	0.6	10.0	9.8	1.8	6.9	6.9	7.7
35	3/6/85	WF-1, SG-3/4, DW	1" Saddles	41	13	270	85.9	49:1	0.8	10.0	9.8	1.4	6.9	6.9	7.7

TABLE 8 - TABULATION OF EXPERIMENTAL RUNS - 57-INCH DIAMETER COLLINS

Run No.	Date	Water Source	Packing Type	Water Flow		Air Flow		Air:Water Vol. Ratio	Column ΔP Inches H ₂ O	Temperatures, °C				Water pH	
				gpm	gpm/ft ²	cfm	cfm/ft ²			Water In	Water Out	Air In	Air Out	In	Out
1	10/24/84	WF-1, SG-2/3/4, DW	3" Saddles	355	20.1	2300	130	48:1	0.7	11.0	11.0	13.6	13	6.6	7.4
3	10/24/84	WF-1, SG-2/3/4, DW	3" Saddles	444	25.1	2130	120	36:1	0.7	11.2	11.2	14.0	13	6.8	7.7
11 (a)	11/19/84	WF-1, SG-2/3/4, DW	3" Saddles	655	37.0	1770	100	20:1	-	11.0	11.7	3.0	4	6.9	7.7
14 (b)	12/14/84	WF-1, SG-2/3/4, DW	3" Saddles	355	20.1	2310	131	49:1	-	11.0	10.1	3.1	7	6.7	7.7
36	4/11/85	WF-1, SG-2/3/4, DW	1" Saddles	405	22.9	1170	66.0	22:1	-	10.3	10.1	9.8	-	6.5	7.4
37	4/11/85	WF-1, SG-3/4	1" Saddles	280	15.8	1380	77.9	37:1	-	10.2	10.0	11.0	-	-	-
38	4/11/85	WF-1, SG-3/4	1" Saddles	230	13.0	1635	92.3	53:1	-	10.4	10.0	13.0	-	-	-
(a) Some water (<200 gpm) pumped from clear well to provide sufficient feed rate.										(b) Return of Run No. 1.					

TABLE 9 - OPERATING DATA ARRANGED FOR DATA ANALYSIS

Data Group	Analysis Number	Packing Size (inch)	Column Diameter (inch)	Air Water Ratio	Loading Air (m ³ m ⁻² sec ⁻¹) Water (m ³ m ⁻² sec ⁻¹)		Run Number
1	1	0.5	6	50.	0.17	0.0034	13
	2	0.5	6	34.	0.16	0.0046	9
	3	0.5	6	20.	0.13	0.0067	8
	4	0.5	6	10.	0.10	0.0098	7
	5	0.5	6	5.0	0.067	0.014	6
	6	0.5	6	5.0	0.067	0.013	12
	7	0.5	6	49.	0.17	0.0035	10
2	8	1.	6	50.	0.44	0.0089	46
	9	1.	6	36.	0.40	0.011	45
	10	1.	6	21.	0.33	0.016	44
	11	1.	6	9.8	0.25	0.026	48
	12	1.	6	5.0	0.15	0.031	47
3	13	1.	12	50.	0.44	0.0088	43
	14	1.	12	36.	0.39	0.011	42
	15	1.	12	21.	0.33	0.016	41
	16	1.	12	9.9	0.25	0.026	40
	17	1.	12	5.0	0.15	0.031	39
4	18	1.	24	49.	0.44	0.0089	35
	19	1.	24	36.	0.39	0.011	34
	20	1.	24	20.	0.32	0.017	33
	21	1.	24	10.	0.26	0.026	32
	22	1.	24	5.0	0.15	0.030	31
5	23	1.	57	53.	0.47	0.0088	38
	24	1.	57	37.	0.40	0.011	37
	25	1.	57	22.	0.34	0.016	36
6	26	2.	6	47.	0.65	0.014	18
	27	2.	6	35.	0.61	0.017	20
	28	2.	6	20.	0.51	0.025	22
	29	2.	6	9.9	0.39	0.039	24
	30	2.	6	5.1	0.26	0.051	26
7	31	2.	12	51.	0.66	0.013	17
	32	2.	12	34.	0.61	0.018	19
	33	2.	12	20.	0.51	0.026	21
	34	2.	12	10.	0.39	0.039	23
	35	2.	12	5.0	0.25	0.051	25
8	36	2.	24	49.	0.66	0.014	30
	37	2.	24	36.	0.61	0.017	29
	38	2.	24	19.	0.50	0.026	28
	39	2.	24	9.9	0.39	0.039	27
9	40	3.	12	48.	0.66	0.014	2
	41	3.	12	35.	0.61	0.017	4
	42	3.	12	20.	0.51	0.026	5
	43	3.	12	48.	0.65	0.014	15
	44	3.	12	37.	0.60	0.016	16
10	45	3.	57	49.	0.66	0.014	14
	46	3.	57	36.	0.61	0.017	3
	47	3.	57	20.	0.51	0.025	11

FLOW LIMITATIONS

Because of flow limitations, some of the planned runs at the lower air:water ratios could not be run. Specifically, the following flow limitations were encountered:

1. With the 57-inch column, the two lower air:water ratios (5:1 and 10:1) could not be run because of the inability of the Village wells to supply the required water flow (670 gpm or 0.96 MGD). Additionally, the liquid distributor at the top of the column was not designed for flows over 600 gpm.
2. With the 24-inch column, the 5:1 air:water ratio could not be run because of flow limitations with the long water hose installation used for the temporary installation with the EPA column.
3. With the 12-inch column and the 3-inch saddle packing, the two lower air:water ratios could not be run because of apparent column flooding (as indicated by a high pressure drop and surging of flows). The flooding was believed to occur at the restrictions caused by the two wall collectors (9.5-inch i.d. or 62.6% of the column cross-sectional area).

PERCENT REMOVAL OF CONTAMINANTS

As a guide to monitoring the overall results of the experimental program, percent removals were calculated for tetrachloroethylene and for the total volatile organic compounds (VOCs). (The total VOCs are the sum of tetrachloroethylene, trichloroethylene, and 1,2 cis-dichloroethylene). The percent removal is defined as:

$$\frac{\text{Inlet Concentration} - \text{Outlet Concentration}}{\text{Inlet Concentration}} \times 100 = \% \text{ Removal}$$

The percent removals for each of the column diameters and packing types (at the various air: water ratios) are shown in Tables 10 through 19. In the last three columns, two numbers are presented; the first number is the value for tetrachloroethylene and the second number is the value for the total VOCs. It can be seen that, with 1/2-inch and 1-inch saddles, percent removals in the order of 99% or more are readily achieved at air:water ratios of 35:1 or higher.

TABLE 10. PERCENT REMOVALS

6" Dia. Column - 1/2" Ceramic Saddles				
Air:Water		Inlet ^(a) (ug/l)	Outlet ^(a) (ug/l)	% Removal
Run No.	Ratio (Nominal)			
6	5:1	44.6/64.1	3.15/12.05	93/81
12	5:1	74.5/104.6	4.9/20.0	93/80.9
7	10:1	48.7/68.0	ND/<3.5	>99.8/>94.9
8	20:1	46.4/64.7	ND/ND	>99.8/>99.5
9	35:1	46.2/64.9	ND/ND	>99.8/>99.5
10	50:1	51.5/70.6	ND/ND	>99.8/>99.6
13	50:1	82.7/122.6	ND/ND	>99.9/>99.8

(a) Tetrachloroethylene/Total VOCs

TABLE 11. PERCENT REMOVALS

6" Dia. Column - 1" Plastic Saddles				
Air:Water		Inlet ^(a) (ug/l)	Outlet ^(a) (ug/l)	% Removal ^(a)
Run No.	Ratio (Nominal)			
47	5:1	188.7/265.2	38.7/82.7	79.5/68.8
48	10:1	181.3/260.9	20.6/46.0	88.6/82.4
44	20:1	196.2/274.3	9.4/15.7	95.2/94.3
45	35:1	196.6/281.0	5.3/7.2	97.3/97.4
46	50:1	201.4/281.8	2.8/3.3	98.6/98.8

(a) Tetrachloroethylene/Total VOCs

TABLE 12. PERCENT REMOVALS

6" Dia. Column - 2" Plastic Saddles				
Air:Water		Inlet (ug/l)	Outlet (ug/l)	% Removal
Run No.	Ratio (Nominal)			
26	5:1	195.8/276.9	40.7/77.5	79.2/72.0
24	10:1	215.3/302.0	23.4/46.5	89.1/84.6
22	20:1	206.6/290.7	10.2/19.4	95.1/93.3
20	35:1	191.5/268.1	4.7/8.5	97.5/96.8
18	50:1	200.4/281.1	3.9/6.6	98.1/97.7

TABLE 13. PERCENT REMOVALS

12" Dia. Column - 1" Plastic Saddles				
Run No.	Air:Water Ratio (Nominal)	Inlet (ug/l)	Outlet (ug/l)	% Removal
39	5:1	125/207	11/40.2	91/80.6
40	10:1	130/222	7.0/21.8	95/90.2
41	20:1	130/214	4.1/9.0	97/96
42	35:1	110/182	0.7/<1.4	>99/>99
43	50:1	110/198	1.6/2.6	99/99

TABLE 14. PERCENT REMOVALS

12" Dia. Column - 2" Plastic TRI-PACKS				
Run No.	Air:Water Ratio (Nominal)	Inlet (a) (ug/l)	Outlet (a) (ug/l)	% Removal (a)
25	5:1	120/187	35/82	71/56
23	10:1	93/167	9.5/26.1	90/84.4
21	20:1	93/149	4.8/10.6	95/92.9
19	35:1	99/188	2.2/4.1	97.7/97.8
17	50:1	77/134	1.4/<2.5	98.2/>98.1

(a) Tetrachloroethylene/Total VOCs

TABLE 15. PERCENT REMOVALS

12" Dia. Column - 3" Plastic Saddles				
Run No.	Air:Water Ratio (Nominal)	Inlet (ug/l)	Outlet (ug/l)	% Removal
5	20:1	24/35.5	4.3/6.6	82/81
4	35:1	25.5/37.1	2.9/4.7	89/87
16	35:1	97.4/165.0	15.7/23.9	84/85.5
2	50:1	25.5/37.3	1.8/3.0	93/92
15	50:1	156.1/220.5	10.7/14.2	93/93.6

TABLE 16. PERCENT REMOVALS

24" Dia. Column - 1" Plastic Saddles				
Run No.	Air:Water Ratio (Nominal)	Inlet (ug/l)	Outlet ^(a) (ug/l)	% Removal
31	5:1	83/142	11/35.4	87/75.1
32	10:1	96/157	4.6/15.9	95/90.0
33	20:1	95/164	1.0/<3.1	99/>98
34	35:1	95/157	0.6/<1.9	99/>98.8
35	50:1	110/189	<0.5/<1.5	>99.5/>99.2

(a) Sample I

TABLE 17. PERCENT REMOVALS

24" Dia. Column - 2" Plastic TRI-PACKS				
Run No.	Air:Water Ratio (Nominal)	Inlet ^(a) (ug/l)	Outlet ^{(a)(b)} (ug/l)	% Removal ^(a)
27	10:1	64/119	21/43	67/64
28	20:1	68/112	6.0/11.6	91/90
29	35:1	88/137	2.3/6.0	97/96
30	50:1	59/98	2.6/5.5	96/94

(a) Tetrachloroethylene/Total VOCs

(b) Sample I

TABLE 18. PERCENT REMOVALS

57" Dia. Column - 1" Plastic Saddles				
Run No.	Air:Water Ratio (Nominal)	Inlet (ug/l)	Outlet (ug/l)	% Removal
36	20:1	94/153	1.2/<3.6	98.7/>97.6
37	35:1	135/225	0.8/<1.8	99.4/>99.2
38	50:1	140/234	0.8/1.4	99.4/99.4

TABLE 19. PERCENT REMOVALS
57" Dia. Column - 3" Plastic Saddles

Run No.	Air:Water Ratio (Nominal)	Inlet (ug/l)	Outlet (ug/l)	% Removal
11	20:1	40/68.4	1.5/<2.9	96/>95.8
3	35:1	24/34.1	0.8/1.3	97/96
14	50:1	72/118	1.6/<2.6	98/98

In order to compare the different column diameters with the same packing material, the results are retabulated in Tables 20, 21, and 22 for the 1-inch saddles, the 2-inch TRI-PACKS, and the 3-inch saddles, respectively. For the 1-inch and 3-inch saddles, the percent removals generally increase with increasing diameter, thus indicating a wall effect with the smaller diameter columns. This same effect is not apparent with the 2-inch TRI-PACKS. A further discussion of the wall effect is presented later in this report.

TABLE 20. PERCENT REMOVALS
PACKING - 1" SADDLES

Air:Water Ratio (Nominal)	6" Column % Repl ^(a)	12" Column % Repl	24" Column % Repl	57" Column % Repl
5:1	79.5/68.8	91/80.6	87/75.1	-
10:1	88.6/82.4	95/90.2	95/90.0	-
20:1	95.2/94.3	97/96	99/>98	98.7/>97.6
35:1	97.3/97.4	>99/>99	>99/>98.8	99.4/>99.2
50:1	98.6/98.8	99/99	>99.5/>99.2	99.4/99.4

(a) Tetrachloroethylene/Total VOCs

TABLE 21. PERCENT REMOVALS
PACKING - 2" TRI-PACKS

Air:Water Ratio (Nominal)	6" Column % Reml	12" Column % Reml	24" Column % Reml
5:1	79.2/72.0	71/56	-
10:1	89.1/84.6	90/84.4	67/64
20:1	95.1/93.3	95/92.9	91/90
35:1	97.5/96.8	97.7/97.8	97/96
50:1	98.1/97.7	98.2/>98.1	96/94

TABLE 22. PERCENT REMOVALS
PACKING - 3" SADDLES

Air:Water Ratio (Nominal)	12" Column % Reml	57" Column % Reml
20:1	82/81	96/>95.8
35:1	89/87 84/85.5	97/96
50:1	93/92 93/93.6	98/98

POWER MEASUREMENTS

Blower power measurements were made for the 6-inch, 12-inch, and 57-inch diameter columns, in accordance with the requirements of the cooperative agreement. However, these power measurements did not prove to be useful for the following reasons:

1. Because of the large range of air flows needed for the experimental runs, the blowers were over designed and the air flow had to be throttled (with a valve) for the experimental runs.
2. The air duct work, in some cases, contained more elbows and other fittings than would be used in a non-experimental installation. The duct work for the 57-inch column, in particular, was somewhat complex because the dual blowers were housed in the pump building.

3. Because of operating convenience, the discharge side of the blower was throttled for flow control. This increased the power consumption by approximately 3% (as compared with throttling the suction side).

Because of the above reasons, the experimental power measurements were excessively high and were not utilized in the data analysis. However, for documentation purposes, the blower power measurements are tabulated in Appendix E.

ENVIRONMENTAL CONDITIONS

Various environmental parameters (such as humidity and air velocity) were measured, in accordance with the requirements of the cooperative agreement. These measurements were not used for data analysis; nevertheless, they are tabulated in Appendix F for documentation purposes.

SECTION 6

DATA ANALYSIS AND DISCUSSION

GENERAL

Analysis of the experimental results was conducted by the EPA-TSD, using programs developed by that organization. The data analysis prepared by the EPA-TSD is presented fully in Appendix A, and the results are summarized herein. Additionally, the theory of mass transfer in a packed column has been well developed in the chemical engineering literature (1,2) and is not repeated herein.

MASS TRANSFER COEFFICIENTS

The mass transfer coefficients resulting from analysis of the experimental data, as described in Appendix A, are summarized in Tables 23, 24, and 25 for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene, respectively. Values for air:water ratios of 20:1, 35:1, and 50:1 are shown, since such ratios are typically used for air-stripping of these VOCs.

It can be seen, generally, that the mass transfer coefficients increase as the column diameter increases (with the same packing material). Putting it another way, the mass transfer coefficients increase as the column diameter:packing size ratio increases. This is to be expected, since the wall effect (i.e., channeling of water on the inside of the column wall) is greater with a smaller diameter column. Of special note, however, is the observation that the mass transfer coefficient continued to increase as the column diameter:packing size ratio was increased from 12:1 and also from 24:1 (for the 1-inch saddles). (Typically, the "rule of thumb" used in designing packed columns is that the column diameter:packing size ratio should be at least 12:1.) Thus, based on these results, it appears that using pilot plant data to design a full-scale column will result in a conservative design.

FULL-SCALE SYSTEM DESIGNS

In designing a full-scale packed column system for a specific requirement (say 99% removal of tetrachloroethylene), there are a number of design parameters, such as packing type, packing size, and air:water ratio, that will achieve the same result. In order to select the cost-optimized

design parameters, the EPA-TSD has developed a cost model that estimates both the capital and operating costs. The capital costs are based on the amount of steel, concrete, packing material, pump capacity, and blower capacity required to achieve a given removal efficiency of a given compound from a given liquid flow at a given temperature. The yearly operational cost is based on the amount of maintenance and electric power required to keep the system in operation. The capital cost is amortized over 20 years and added to the operational cost to produce a yearly cost. The yearly cost is divided by the volume of water treated per year and expressed as cents per 1000 gallons treated. This is referred to as total production cost. The cost model is described in Appendix A along with its limitations and qualifications.

Using the data obtained from the four different diameter columns, cost-optimized designs were developed as detailed in Appendix A. The design criteria used were as follows:

99% removal of tetrachloroethylene
 350 gpm (0.5 MGD) design flow
 9 deg C water temperature
 5.8 cents per kw hr power cost
 10% interest rate
 1.2 safety factor for Henry's coefficient
 1.2 safety factor for mass transfer coefficient

The results for the 1-inch plastic saddles and air:water ratios of 20:1 to 50:1 are summarized in Table 26.

TABLE 23. MASS TRANSFER COEFFICIENTS FOR TETRACHLOROETHYLENE

Column Diameter (Inches)	Packing Type	Column Dia: Packing Size Ratio ^(a)	Mass Transfer Coefficients (sec ⁻¹)		
			Air:Water Ratio		
			20:1	35:1	50:1
6	1" Saddles	6:1	0.0086	0.0065	0.0064
12	1" Saddles	12:1	0.012	0.012	0.0078
24	1" Saddles	24:1	0.015	0.012	0.0099
57	1" Saddles	57:1	0.035	0.017	0.014
6	2" TRI-PACKS	3:1	0.015	0.012	0.010
12	2" TRI-PACKS	6:1	0.016	0.014	0.010
24	2" TRI-PACKS	12:1	0.013	0.016	0.028
12	3" Saddles	4:1	0.0091	0.0064	0.0066
57	3" Saddles	19:1	0.015	0.010	0.0086

(a) This is a nominal ratio, since "packing size" is not a definitive number (for example, 1-inch plastic saddles measure approximately 1.7 inches across their largest dimension).

TABLE 24. MASS TRANSFER COEFFICIENTS FOR TRICHLOROETHYLENE

Column Diameter (inches)	Packing Type	Column Dia.: Packing Size Ratio	Mass Transfer Coefficients (sec^{-1})		
			Air To Water Ratio		
			20:1	35:1	50:1
6	1" saddles	6:1	0.0099	0.0085	0.0087
12	1" saddles	12:1	0.013	0.013	0.0089
24	1" saddles	24:1	0.015	0.013	0.010
57	1" saddles	57:1	0.036	0.025	0.021
6	2" TRI-PAKS	3:1	0.013	0.010	0.0084
12	2" TRI-PAKS	6:1	0.017	0.015	0.010
24	2" TRI-PAKS	12:1	0.012	0.015	0.023
12	3" saddles	4:1	0.0099	0.0054	0.0058
57	3" saddles	19:1	0.017	0.0086	0.0078

TABLE 25. MASS TRANSFER COEFFICIENTS FOR CIS-1,2 DICHLOROETHYLENE

Column Diameter (inches)	Packing Type	Column Dia.: Packing Size Ratio	Mass Transfer Coefficients (sec^{-1})		
			Air To Water Ratio		
			20:1	35:1	50:1
6	1" saddles	6:1	0.0085	0.0079	0.0079
12	1" saddles	12:1	0.013	0.012	0.0089
24	1" saddles	24:1	0.015	0.011	0.0094
57	1" saddles	57:1	0.014	0.020	0.019
6	2" TRI-PAKS	3:1	0.013	0.012	0.011
12	2" TRI-PAKS	6:1	0.015	0.016	0.012
24	2" TRI-PAKS	12:1	0.017	0.013	0.023
12	3" saddles	4:1	0.010	0.0065	0.0069
57	3" saddles	19:1	0.019	0.010	0.010

TABLE 26. DESIGN PARAMETERS AND COST ESTIMATES RESULTING FROM COST
MODEL FOR 1-INCH PLASTIC SADDLES

Column Diameter (inches)	Air: Water Ratio	Diameter (inches)	Packing Height (feet)	Cost Estimate (1982 Dollars)		
				Capital (K\$)	Operating (K\$/year)	Production /1000 gal)
6	50.	70.	27.	140.	7.2	13.
6	36.	63.	34.	140.	7.4	13.
6	21.	52.	40.	130.	7.2	12.
12	50.	70.	22.	120.	6.6	12.
12	36.	63.	18.	110.	5.6	9.9
12	21.	52.	28.	110.	6.0	10.
24	49.	70.	17.	110.	6.1	11.
24	36.	63.	18.	110.	5.7	10.
24	20.	51.	24.	100.	5.5	9.6
57	53.	70.	12.	98.	5.4	9.2
57	37.	63.	13.	94.	5.0	8.8
57	22.	53.	9.6	80.	4.1	7.4

From these results, the following cost-optimized parameters would probably be selected:

Test Column Diameter (inches)	Air: Water Ratio	Full-Scale Design		Est. Production Cost (¢/1000 gal)
		Column Diameter (inches)	Packing Height (feet)	
6	20:1	52	40	12
12	20:1	52	28	10
24	20:1	51	24	9.6
57	20:1	53	9.6	7.4

Thus, once again, a full-scale system designed from pilot plant data will probably result in a conservative design.

It should be noted that the actual construction costs for the 57-inch packed column system (Table 2) is significantly higher than the estimated capital costs resulting from the cost model. This is to be expected, since there are many items and features (such as building, large clearwell, dual blowers, dual pumps, chemical feed system, etc.) that are not included in the cost model. These items and features were site-specific for the Brewster facility because of the prevailing operating conditions of the Brewster water supply system, the need to replace the existing wellfield pumping station, and the design engineers' philosophy regarding sheltering of operating equipment (air blowers, pumps, electrical equipment, etc.) from inclement weather conditions. In more favorable climates, a packed column system configuration similar to that adopted by the EPA-TSD for the cost model would most likely be utilized.

ECONOMIC COMPARISON OF PACKING MATERIALS

Comparison of the minimum production cost (for the same column diameter) was made for the different packing types. The results of the minimum estimated production costs resulting from the EPA-TSD cost model are summarized in Table 27. Comparing the different packing materials in the same diameter column, the 2-inch TRI-PACKS gave the lower production cost, the 1-inch saddles are intermediate, and the 3-inch saddles gave the higher production cost.

It should be noted, again, that these cost comparisons are subject to the limitations and qualifications presented in Appendix A. For example, these economic comparisons were made at only one air pressure drop gradient (1-inch water). Different air pressure drop gradients may be more economical for the different packing materials. The results of this economic comparison should be used only as a general comparison.

TABLE 27. COMPARISON OF MINIMUM PRODUCTION COST FOR DIFFERENT PACKING MATERIALS

Column Dia. (inch)	Packing Type	Minimum Est. Production Cost (¢ /1000 gal)
12	1" saddles	9.8
24	1" saddles	9.6
57	1" saddles	7.4
12	2" TRI-PACKS	9.7
24	2" TRI-PACKS	7.9
12	3" saddles	12
57	3" saddles	9.6

ONDA MASS TRANSFER COEFFICIENTS

Mass transfer coefficients were calculated using Onda's mass transfer coefficient model ⁽²⁾. These results are presented in Appendix A, and an example calculation is shown in Table 10 of that Appendix.

The mass transfer coefficients predicted by the Onda correlation are compared, in Tables 28, 29, and 30, with the best fit experimentally derived results for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene, respectively. Generally, but not always, the two values are in reasonably good agreement. Based on these results, it appears that the Onda correlation would tend to give a conservative design for a full-scale system.

TABLE 28. MASS TRANSFER COEFFICIENTS FOR TETRACHLOROETHYLENE
Mass Transfer Coefficients (sec^{-1})

Col. Dia. (in.)	Packing Size (in.)	Air:Water Ratio									
		5:1		10:1		20:1		35:1		50:1	
		Exp	Onda	Exp	Onda	Exp	Onda	Exp	Onda	Exp	Onda
6	0.5	0.013	0.015	0.010	0.013	0.0094	0.010	0.0075	0.0077	0.0085	0.0062
6	1	0.011	0.019	0.012	0.017	0.0086	0.012	0.0065	0.0093	0.0064	0.0079
12	1	0.025	0.019	0.021	0.017	0.012	0.012	0.012	0.0092	0.0078	0.0078
24	1	0.017	0.019	0.020	0.017	0.015	0.012	0.012	0.0090	0.0099	0.0078
57	1	-	-	-	-	0.035	0.012	0.017	0.0091	0.014	0.0079
12	3	-	-	-	-	0.0091	0.014	0.0064	0.011	0.0066	0.0092
57	3	-	-	-	-	0.015	0.014	0.010	0.011	0.0086	0.0092

TABLE 29. MASS TRANSFER COEFFICIENTS FOR TRICHLOROETHYLENE

Col. Dia. (in.)	Packing Size (in.)	Mass Transfer Coefficients (sec^{-1})									
		Air:Water Ratio									
		5:1		10:1		20:1		35:1		50:1	
		Exp	Onda	Exp	Onda	Exp	Onda	Exp	Onda	Exp	Onda
6	0.5	0.0048	0.015	0.0071	0.013	0.0061	0.010	0.0030	0.0079	0.0080	0.0064
6	1	0.0088	0.019	0.010	0.018	0.0099	0.013	0.0085	0.0097	0.0087	0.0083
12	1	0.029	0.019	0.022	0.018	0.013	0.013	0.0013	0.0097	0.0089	0.0082
24	1	0.018	0.019	0.021	0.018	0.015	0.013	0.013	0.0094	0.010	0.0082
57	1	-	-	-	-	0.036	0.012	0.025	0.0095	0.021	0.0082
12	3	-	-	-	-	0.0099	0.014	0.0054	0.011	0.0058	0.0094
57	3	-	-	-	-	0.017	0.014	0.0086	0.011	0.0078	0.0094

TABLE 30. MASS TRANSFER COEFFICIENTS FOR CIS-1,2 DICHLOROETHYLENE

Col. Dia. (in.)	Packing Size (in.)	Mass Transfer Coefficients (sec^{-1})									
		Air:Water Ratio									
		5:1		10:1		20:1		35:1		50:1	
		Exp	Onda	Exp	Onda	Exp	Onda	Exp	Onda	Exp	Onda
6	0.5	0.0082	0.012	0.0050	0.011	0.0067	0.0092	0.0044	0.0074	0.0092	0.0061
6	1	0.0017	0.018	0.0073	0.017	0.0085	0.013	0.0079	0.0098	0.0079	0.0085
12	1	0.013	0.018	0.022	0.017	0.013	0.013	0.012	0.0098	0.0089	0.0084
24	1	0.032	0.018	0.024	0.017	0.015	0.013	0.011	0.0096	0.0094	0.0084
57	1	-	-	-	-	0.014	0.012	0.020	0.0097	0.019	0.0084
12	3	-	-	-	-	0.010	0.013	0.0065	0.010	0.0069	0.0089
57	3	-	-	-	-	0.019	0.012	0.010	0.010	0.010	0.0089

EFFECT OF TEMPERATURE ON OPERABILITY

Even though the experimental runs were made during both winter and summer months, the water temperature stayed within a fairly narrow range. The water temperature into the packed columns ranged from approximately 9 degrees to 12 degrees C over the course of all the runs (see Tables 5-8). This relatively constant temperature was due, of course, to the consistency of the groundwater temperature. Additionally, the ambient air temperature did not significantly impact the water temperature within the column. For example, in the runs when the ambient air temperature was near or below freezing, the water temperature (from the inlet to the outlet of the column) did not drop by more than 1 degree C.

The 57-inch column was run continuously through periods of sub-freezing weather, and the low air temperatures did not interfere with the operation of the packed column. (In fact, since February of 1985, the full-scale column has been "on-stream", and the product water has been used by the Village of Brewster as its public water supply).

The only problem encountered with low temperatures was with the copper tubing sample lines; some of these lines split open during the night-time, even though the sample valves were left partly open. For any future designs, it is recommended that any such sample lines be insulated to prevent freezing in the line.

HENRY'S COEFFICIENT

Henry's coefficient, a physical-chemical property that expresses the volatility of a particular VOC, is dependent on the temperature and the molecular properties of the VOC. For each of the experimental runs, Henry's coefficient was determined by EPA-TSD, and the values are listed on the concentration profiles (lower left-hand corner) in Appendices B, C, and D.

An attempt was made to correlate Henry's coefficient with temperature but was unsuccessful because of scatter in the data. Instead, a best-fit Henry's coefficient was determined (see Appendix A), and these values were 0.30, 0.21, and 0.094 atm m^3 water/ m^3 air for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene, respectively. The inability to arrive at any satisfactory correlation for Henry's coefficient may be due, in part, to the relatively narrow range of temperatures encountered, as discussed above.

REFERENCES

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2. Perry, R. H. and Chilton, C. H., Chemical Engineers' Handbook, McGraw Hill Book Co., New York, New York, pp. 18-35 and 18-38, Fifth Edition, 1973.

APPENDIX A

DATA ANALYSIS REPORT BY EPA-TSD

FIELD EVALUATION OF PACKED COLUMN AIR STRIPPING, BREWSTER, NEW YORK*

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Introduction:

The contamination of ground water by various low molecular weight volatile organic compounds (VOCs) has been reported in many areas of the country. The frequency of such reports is increasing as more drinking waters are being analyzed for these types of compounds. As part of its mission in implementing the Safe Drinking Water Act, the Office of Drinking Water within the Environmental Protection Agency (EPA) evaluates treatment processes for removing organic compounds from drinking waters.

The Office of Drinking Water's strategy for developing drinking water regulations includes consideration of treatment methods and economics before regulating a particular compound. The high volatility of the VOCs indicates that air stripping is a process that should be applicable. The Technical Support Division, Office of Drinking Water, within EPA is conducting a series of studies to field verify engineering design parameters and economics for air stripping VOCs from ground waters. This report is part of a series that describes that work. Specifically, this report describes a field evaluation conducted at Brewster, NY.

Summary:

An evaluation was conducted to determine the effect of column diameter on mass transfer coefficients. Four pilot packed column air stripping systems were evaluated. The diameters ranged from 6 inches to 57 inches. It was found that mass transfer coefficients increase with column diameter.

Full scale systems were designed using mass transfer coefficients from each pilot system. It was found that using mass transfer coefficients from small scale pilot systems to design full scale systems resulted in over designs. This indicates that there is a safety factor in using mass transfer coefficients from small scale pilot systems to design full scale systems.

Background:

The Village of Brewster, located in Putnam County in southeast New York State, has a population of 1,650. The water supply system consists of wells with individual pumping capacities from 0.00063 to 0.0063 m³ sec⁻¹ (10 to 100 gallons per minute). The maximum daily production of the well fields is 0.022 m³ sec⁻¹ (0.5 million gallons per day (MGD)).

In 1978, the Village of Brewster discovered that one water supply well was contaminated with vinyl chloride, cis- and/or trans-1,2-dichloroethylene, trichloroethylene, tetrachloroethylene, and several other compounds. The concentrations ranged from 5-10, 40-80, 30-60, and 400-600 ug L⁻¹, respectively.

In 1979, the Village, with a grant from New York State, contracted with N.L. Jacobson and Associates, consulting engineers, to investigate treatment alternatives. Lagoon spray aeration was tested, found to be promising, but the treatment objective of 99% tetrachloroethylene removal could not be obtained.

In 1981, N.L. Jacobson, with technical assistance from EPA, Office of Drinking Water, Technical Support Division (TSD), designed and constructed a pilot packed column air stripping system. The pilot system consisted of a 0.30 m (12 inch) diameter column packed with 5.5 m (18 feet) of 0.025 m (1 inch) plastic saddles. Tetrachloroethylene removal efficiencies of 99% were obtained in the pilot system.

In 1982, TSD conducted a field evaluation using a 0.61 m (24 inch) diameter pilot packed column air stripping system. Using data from the 0.30 m (12 inch) pilot system and the TSD pilot system, a 0.022 m³ sec⁻¹ (0.5 MGD) full scale system was designed. The full scale system consisted of one 1.4 m (57 inch) diameter column packed with 5.4 m (17'-9") of 0.025 m (1 inch) plastic saddles. The design air flow was 0.72 m³ sec⁻¹ (1,530 standard cubic feet per minute (SCFM)) giving an air to water ratio of 33 to 1.

Later in 1982, the Village applied for and received a cooperative agreement with EPA, Office of Research and Development, Drinking Water Research Division to investigate and confirm scale-up capability of an air-stripping packed column from pilot scale to full scale.

Packed Column Air Stripping Process:

If water contaminated with volatile organic compounds (VOCs) is brought in contact with uncontaminated air, some of the VOC molecules will transfer to the air. In the packed column air stripping process, this transfer is facilitated as air and water are continuously replenished and mixed together in a countercurrent flow pattern (see Figure 1).

- (1) Contaminated water is pumped to the top of a column, distributed at the top, and cascaded down through a bed of packing material.
- (2) Uncontaminated air is blown in at the bottom of the column and forced up through the same bed of packing material.
- (3) Packing material provides a combination of a large surface area to provide mixing of air and water, contact time for VOC molecules to transfer from water to air, and a large void volume to minimize energy loss of the air system.

- (4) As contaminated water cascades down through the column VOC molecules are transferred to the air.
- (5) Air and VOCs are released to the atmosphere at the top of the column. The concentration of VOC in air released at the top of the column is less than the original concentration of VOC in water due to the large air to water volume ratio. The concentration of VOCs in air is further reduced by dispersion into the atmosphere.
- (6) The countercurrent flow process provides mixing of the most contaminated air and water at the top of the column and mixing of the cleanest air and water at the bottom of the column. The countercurrent flow pattern provides the highest removal efficiencies possible.

Figure 2 illustrates air to water ratios as a function of liquid and air loadings. The upper loading limit at which a packed column can be operated is the combination of liquid and air loadings that force the down flowing water to become entrapped in the upflowing air. This is generally called flooding. The flooding line for 0.025 m (1 inch) plastic saddles at 9 deg C is shown in Figure 2. Packed columns can be operated anywhere below the flooding line. The theory of mass transfer for a packed column applies to this full range. However, the available empirical models are limited to much smaller ranges.

Mass Transfer Theory:

The theory of mass transfer in a packed column has been well developed in the chemical engineering literature (Ref 1). From mass transfer theory, the author developed equation 1 which can be used to predict the liquid phase concentration at any point along the packing height. There are a total of nine (9) terms in equation 1 required to predict the liquid phase concentration (X).

Concentration Profile with Unstrippable Component:

$$X = X_t * ((X_u * (1-C)) + C) \dots\dots\dots \text{eq. 1}$$

Where :

$$C = ((R * A) - 1) / ((R * B) - 1)$$

$$A = \text{EXP}((Z_t - Z) * (K_{la}/L) * ((R-1)/R))$$

$$B = \text{EXP}(Z_t * (K_{la}/L) * ((R-1)/R))$$

$$R = (G / L) * (H / P_t)$$

Xt: VOC concentration at top of packing ($\mu\text{g L}^{-1}$). The concentration at the top of the packing material (Xt) should not be confused with the raw water concentration. There may be some VOC loss as water travels through the well pump, the piping between the well and the air stripping system, and the liquid distribution system at the top of the packed column. This VOC loss is collectively referred to as the influent end effect.

- Xu: VOC unstrippable component (fraction of X_t). The unstrippable component (X_u) is used to account for anomalies that are observed in real systems. The unstrippable component may be due to short circuiting of water through the packed column, background VOC contamination in the influent air, a physical or chemical complex holding the VOC in the liquid phase, cross contamination of sample bottles, or other unknown phenomenon. In general the unstrippable component is a fraction of X_t that, for some reason or another, can not be removed by the air stripping process at even the highest air to water ratios or the tallest packing heights.
- G: Air loading ($m^3 m^{-2} sec^{-1}$). The air loading term (G) is the total air flow through the column per unit of cross-sectional area of the column.
- L: Liquid loading ($m^3 m^{-2} sec^{-1}$). The liquid loading term (L) is the total liquid flow through the column per unit of cross-sectional area of the column.
- H: Henry's coefficient (atm m^3 water m^{-3} air). Henry's coefficient (H) is a physical-chemical property that expresses the volatility of the particular VOC. Henry's coefficient is dependent only on the temperature and molecular properties of the VOC and not dependent on the other eight (8) terms in equation 1.
- Pt: Operating pressure (1 atm). The operating pressure (Pt) is generally 1 atmosphere.
- Zt: Packing height (m). The term Zt is the total height of the packing material.
- Z: Location within column measured from top of column (m). The term Z is the vertical location within the column measured from the top of the packing material.
- Kla: Mass transfer coefficient (sec^{-1}). The mass transfer coefficient (Kla) expresses the overall rate of VOC transfer from the liquid phase to the air phase. The mass transfer coefficient is dependent on the VOC molecular properties, packing material properties, liquid loading, and air loading. The mass transfer coefficient is not dependent on the concentration terms X_t and X_u or the packing height terms Zt and Z.
- X: Predicted VOC concentration ($ug L^{-1}$). The predicted VOC concentration is a function of the other nine parameters above.

Objectives:

The main objective of the cooperative agreement was to investigate using data from small scale pilot systems to design full scale systems. A

secondary objective was to evaluate different packing materials. A third objective was to evaluate the mass transfer coefficients predicted by the Onda correlation.

Experimental Design:

The main objective was met by using four packed columns. Each of the four packed columns were identical as possible except for the diameters. The diameters were 0.15, 0.30, 0.61, and 1.4 m (6, 12, 24 and 57 inches). All four columns were packed with 0.025 m (1 inch) plastic saddles and operated at identical liquid and air loadings. In addition to 0.025 m (1 inch) plastic saddles, 0.012 m (0.5 inch) ceramic saddles, 0.051 m (2 inch) Tri-Pack plastic spheres, and 0.076 m (3 inch) plastic saddles were evaluated.

The cost to remove 99% tetrachloroethylene from a $0.022 \text{ m}^3 \text{ sec}^{-1}$ (0.5 MGD) contaminated ground water source was used as an evaluation statistic.

Field Evaluation:

The Technical Support Division has designed and constructed a portable pilot packed column air stripping system. The system, shown in Figure 3, consists of a 7.3 m (24 ft) tall, 0.6 m (2 ft) diameter aluminum column packed with 5.5 m (18 ft) of 0.025 m (1 inch) plastic saddles. Eighteen sample ports were installed at 0.3 m (1 ft) intervals along the column height to sample the center 0.3 m (1 ft) of the column. This sampling system permits monitoring the concentration profile of VOCs along the column height. The pilot system was constructed in 0.91 m (3 ft) tall sections to facilitate transportation to the field sites.

At Brewster, NY a 0.05 m (2 inch) fire hose was used to connect the water system to the influent line of the pilot system. Mounted on the influent line of the pilot system was a control valve, orifice plate, and mercury manometer that was used to control and monitor the liquid flow. Water was pumped through the liquid flow control system to the top of the pilot system. At the top of the pilot system were four upturned 0.05 m (2 inch) elbows which distributed the liquid flow onto the top of the packing material. Water cascaded down through the packing material and was collected in an effluent tank at the bottom of the column. A 0.1 m (4 inch) fire hose was used to discharge the effluent water to a field.

Influent air was drawn into the pilot system at the bottom of the column. The air cascaded up through the packing material to the top of the column and was returned to ground level through an 0.15m (6 inch) airduct. Mounted inside the air duct was a pitot tube and control damper to monitor and control air flow. Following the control damper the air duct was connected to the intake side of a blower. Air was discharged at ground level 15 m (50 feet) down wind from the air intake. Water manometers were installed above the top of packing material and at the pitot tube to measure air pressure. A thermometer was installed above the top of the packing material to measure air temperature.

An influent sample port was installed in front of the liquid control valve to collect influent samples. Nine of the eighteen sample ports installed inside the packed column were used. The nine sample ports that were used were selected at 0.6 m (2 feet) intervals such that the concentration of the VOCs could be measured as water passed through the packed column. The sample ports were designed such that air was not withdrawn with the sample. The pilot system was operated at steady state for 30 minutes before samples were taken.

The 0.15, 0.30, and 1.4 m (6, 12 and 57 inch) diameter columns were designed by N.L. Jacobson. All four columns were constructed as identical as possible except for the column diameter and slight variations in the sample port location. The location of the sample ports and identification letters are shown in Table 1.

The liquid and air loadings were selected such that the air pressure drop gradient through all columns and packing materials was held constant at $50 \text{ N m}^{-2} \text{ m}^{-1}$ (1/16 inch water column per foot of packing height). The original plan was to operate all four columns and all four packing materials at 50:1, 35:1, 20:1, 10:1, and 5:1 air to water ratios. However, the maximum pumping capacity limited the flow. Despite the flow limitations, each column and each packing material was operated at air to water volume ratios of 50:1, 35:1, and 20:1. In addition to these three air to water ratios the 0.15 and 0.30 m (6 and 12 inch) columns were operated at 10:1 and 5:1. The 0.61 m (24 inch) column was operated at 10:1 and 5:1 using 0.025 m (1 inch) plastic saddles and 10:1 using 0.051 m (2 inch) Tri-Pack packing.

Table 2 presents the operating data from this field evaluation. Table 2 includes the packing size, pilot column size, air to water ratio, air loading, and liquid loading. During the field evaluation run numbers were assigned in chronological order. The field run numbers are shown in Table 2 in the column labeled Field Run Number. There were a total of 48 runs conducted. However, field run number 1 was a shake down run and not included in Table 2 or the following data analysis. For the purpose of analyzing the data, the runs were sorted and assigned an analysis number as shown in Table 2 in the column labeled Analysis Number. All data resulting from one operating condition were collectively referred to as a RUN and have a unique analysis number. All data resulting from the same column using the same packing material were collectively referred to as a data GROUP. Group numbers are shown in Table 2 in the column labeled Data Group. All data resulting from one compound were collectively referred to as a data SET. The tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene data sets are shown in Table 3, 4, and 5, respectively.

The concentration profile data for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene are plotted in Appendix B, C, and D, respectively.

Data Analysis:

The data analysis adjusted parameters in equation 1 such that equation 1 best fit the three data sets. The parameters were as follows.

- 1) The Henry's coefficients that best fit each data set were determined.
- 2) The unstrippable fraction that best fit each data group were determined.
- 3) The mass transfer coefficients and top of packing concentrations that best fit each run were determined.

In this report the square root of the mean square error (Sq_mse) between the measured concentration and predicted concentration was used in determining the best fit parameters. The minimum Sq_mse was found by adjusting the parameters using a specially developed non-linear multiregression procedure. The procedure implemented the above assumptions. The Sq_mse was computed using the logarithmic form shown in equation 2.

Square Root of Mean Squared Error:

$$Sq\_mse = \text{SQR}((\text{Ln}(X_i) - \text{Ln}(X))^2 / N) \dots\dots\dots \text{eq. 2}$$

Where:

- Sq_mse = Square root of mean squared error
- SQR = Square root function
- Ln = Base e logarithm
- X = Predicted concentration from equation 1
- X_i = Concentration data point from pilot system
- N = Number of data points in:
 - Data Run for X_t and K_{La}
 - Data Group for X_u
 - Data Set for Henry's coefficient

The best fit Henry's coefficient for each data set were 0.30, 0.21, and 0.094 atm m^3 water m^{-3} air for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene, respectively.

The unstrippable fraction was found to be insignificant for all but two data groups. The data group representing the 0.61 m (24 inch) diameter column with 0.051 m (2 inch) plastic Tri-Packs and the data group representing the 1.4 m (57 inch) diameter column with 0.025 m (1 inch) plastic saddles were found to have an unstrippable fraction that averaged 0.016 and 0.033, respectively. The unstrippable fraction was probably due to short circuiting water through the column and packing material.

The best fit mass transfer coefficients for each run in the tetrachloroethylene data set are shown in Table 6. As expected, Table 6 indicates that the mass transfer coefficients increased as the air to water ratio decreased. Table 6 also indicates that for any given packing material the mass transfer coefficients generally increased with increasing column diameter. This increase in mass transfer coefficient is probably due to the column wall interfering with the mass transfer process in the smaller diameter columns. As the ratio of column cross section to perimeter increased the column wall interference was less significant to the overall mass transfer process. The same is true for the best fit mass transfer coefficients for trichloroethylene and cis-1,2-dichloroethylene as shown in Table 7 and 8, respectively.

The best fit top of packing concentration for each run in each data set were also computed. Appendix B, C, and D include the four best fit parameters, square root of the mean squared error, and best fit concentration profile resulting from this data analysis. Viewing appendices 2, 3, and 4 illustrates that the best fit concentration profiles do in fact represent the field data.

The fraction of tetrachloroethylene remaining in the effluent were computed from equation 1 using the best fit parameters. The computed fraction remaining values are shown in Table 6. As expected the fraction remaining increased as the air to water ratio decreased. Although the fraction remaining data show some scatter, in general the fraction remaining decreased as the column diameter increased. This indicates that the removal efficiency increased as the column diameter increased despite the fact that the same air loading, liquid loading, and packing material were used. This is true for the 0.025 m (1 inch), 0.050 m (2 inch), and 0.076 m (3 inch) packing materials.

Full Scale System Designs:

The significance of the above observations are best illustrated by using the results from each run in the tetrachloroethylene data set to design and estimate the cost of a full scale system. The design criteria selected in 1982 were as follows.

- 1) 99% Removal of tetrachloroethylene
- 2) $0.022 \text{ m}^3 \text{ sec}^{-1}$ (0.5 MGD) design flow
- 3) 9 deg C temperature
- 4) 5.8 cents per Kw Hr power cost
- 5) 10% interest rate
- 6) 1.2 safety factor for Henry's coefficient
- 7) 1.2 safety factor for mass transfer coefficient

In order to perform economic evaluations of packed column air stripping and to generate cost optimized design parameters, a cost model was developed by TSD. The cost model, as with any cost model, cannot be universally applied without a critical examination of its components. Many different configurations of pumps, blowers, construction materials, and other items have been suggested and are workable. Many assumptions had to

be made that may not be the optimum solution from one site to another site or from one design engineer's opinion to another engineer's opinion. The packed column air stripping configuration shown in Figure 4 is the result of many discussions with designers, suppliers, and operators. It should not be interpreted as the only configuration that will work or even a recommended system. The best configuration at any particular site will be dependent on specific site capabilities. The cost model used in this report was originally developed for a single well producing 50 to 2000 gallons per minute (gpm). The original model is also discussed in "Economic Evaluation of Trichloroethylene Removal from Contaminated Ground Water by Packed Column Air Stripping" (Ref 2).

The economic analysis estimates both the capital and operating costs. The capital costs are based on the amount of steel, concrete, packing material, pump capacity, and blower capacity required to achieve a given removal efficiency of a given compound from a given liquid flow at a given temperature. The yearly operational cost was based on the amount of maintenance and electric power required to keep the system in operation. The capital cost was amortized over 20 years and added to the operational cost to produce a yearly cost. The yearly cost was divided by the volume of water treated per year and expressed as cents per 1000 gallons treated. This is referred to as total production cost.

The Henry's coefficients and mass transfer coefficients resulting from this data analysis for tetrachloroethylene were used in sizing the following systems. It should be noted that the water temperature during the field evaluation averaged 11 deg C. For the purpose of sizing these systems the unstrippable fraction was assumed to be zero. The air pressure drop as measured in the field was used to estimate the blower operating cost. The resulting system sizes and cost estimates are shown in Table 9.

Using data group 2 as an example, 99% removal can be obtained using any of air to water ratios. As shown in table 9, selecting an air to water ratio of 50:1 results in a column diameter of 1.8 m (70 inch) and packing height of 8.2 m (27 ft.). Reducing the air to water ratio to 5:1 results in a column diameter of 0.96 m (38 inch) and packing height of 52 m (170 ft.). Both these systems should remove 99% tetrachloroethylene. This illustrates that selecting different air to water ratios can result in very different column diameters and packing heights. The selection of which air to water ratio to use should be based on the overall system cost.

The estimated costs for the group 2, 50:1 system, are \$140,000 capital and \$7,200 per year operating. Amortizing the capital cost over 20 years, adding the operating cost, and dividing by the yearly volume of water treated results in a production cost of 13 cents per 1000 gallons. Likewise the estimated costs for the 5:1 system are \$240,000 capital, \$17,000 operating, and 25 cents per 1000 gallons treated. Between the 50:1 and 5:1 systems there exists a minimum production cost.

If a full scale system were designed using data from the 0.15 m (6 inch) diameter pilot column then an air to water ratio of 20:1 would probably be selected as the minimum production cost. The system sizing

would result in a 1.3 m (52 inch) diameter column with 12 m (40 ft) of packing and a production cost of 12 cents per 1000 gallons treated.

If a full scale system were designed using data from the 0.30 m (12 inch) diameter pilot column then an air to water ratio of 20:1 would also probably be selected as the minimum production cost. The system sizing would result in a 1.3 m (52 inch) diameter column with 8.5 m (28 ft) of packing and a production cost of 10 cents per 1000 gallons treated.

If a full scale system were designed using data from the 0.61 m (24 inch) diameter pilot system then an air to water ratio of 20:1 would also be selected as the minimum production cost. The system sizing would result in a 1.3 m (51 inch) diameter column with 7.3 m (24 ft) of packing and a production cost of 9.6 cents per 1000 gallons treated.

If a full scale system were designed using data from the 1.4 m (57 inch) diameter system then an air to water ratio of 20:1 would still be selected as the minimum production cost. The system sizing would result in a 1.3 m (53 inch) diameter column with 2.9 m (9.6 ft) of packing and a production cost of 7.4 cents per 1000 gallons treated.

In all the above cases the cost optimized air to water ratios were the same. As the diameter of the pilot system increased, the required packing height declined along with the estimated cost. Using data from smaller pilot systems thus produced higher packing heights than necessary. Note that the 1.4 m (57 inch) diameter column is a full scale system and did in fact produce higher mass transfer coefficients than the other three columns. Thus, a full scale system designed from a smaller pilot system will probably be a conservative design.

Comparison of Packing Materials:

Comparison of the production cost resulting from using different packing materials is made using the same column diameter. In the 0.15 m (6 inch) diameter column the 0.012 m (0.5 inch) ceramic saddles indicated a minimum production cost of 16 cents per 1000 gallons treated whereas the 0.025 m (1 inch) plastic saddles indicated a minimum production cost of 12 cents per 1000 gallons treated. Thus, 0.025 m (1 inch) plastic saddles are probably more economical.

Comparing the minimum production cost of the 0.05 m (2 inch) Tri-Packs to the 0.025 (1 inch) saddles indicated 10 vs 12, 9.7 vs 9.8, and 7.9 vs 9.6 in the 0.15, 0.30, and 0.61 m (6, 12, and 24 inch) diameter columns. Thus, the 0.05 m (2 inch) Tri-Packs are probably more economical than the 0.025 m (1 inch) plastic saddles.

Comparing the minimum production cost of the 0.076 m (3 inch) saddles to the 0.025 (1 inch) saddles indicated 12 vs 9.8 and 9.6 vs 7.4 in the 0.30 and 1.4 m (12 and 57 inch) diameter columns. Thus, the 0.025 m (1 inch) plastic saddles are probably more economical than the 0.076 m (3 inch) plastic saddles.

It should be noted that these economic comparisons were made at only one air pressure drop gradient, $50 \text{ N m}^{-2} \text{ m}^{-1}$. Different air pressure drop gradients may be more economical for the different packing materials. The results of this economical comparison should only be used as a general comparison.

Onda's Mass Transfer Coefficient Model:

The author has found that the mass transfer coefficient correlation developed by Onda (Ref 3), in general, provides a good agreement with field data. The Onda correlation requires 20 inputs. Of the 20 inputs only the liquid and air loadings can be selected by the designer. The other 18 inputs are fixed for a given temperature, compound, and packing material. An example calculation of the Onda correlation for tetrachloroethylene in a bed of 1 inch plastic saddles at 9 deg C is shown in Table 10. The input parameters are also included in Table 10.

Tables 11, 12, and 13 contain the mass transfer coefficients predicted by the Onda correlation for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene. Comparing the best fit mass transfer coefficients from Tables 6, 7, and 8 for the 0.025 m (1 inch) plastic saddles indicates that the mass transfer coefficient predicted by the Onda correlation were close to the mass transfer coefficient obtained in the 0.30 m (12 inch) diameter column.

Based on this field evaluation, it is expected that a full scale system will have higher mass transfer coefficients than predicted by the Onda correlation. Thus, the design engineer can use the Onda correlation and be confident that a full scale system will be capable of achieving the desired removal efficiency. The designer should be aware that other problems can arise such as poor distribution of air and water that can degrade the actual packed column performance.

Conclusions:

This field evaluation demonstrated that the mass transfer coefficients from a pilot system increase with the column diameter. Further, using data from a small scale pilot system to design a full scale system will produce larger and more expensive equipment than necessary. However, it is possible that the full scale system can perform better than expected if uniform flow distribution can be maintained over the cross section area of the column.

The 0.025 m (1 inch) plastic saddles appeared to be more economical than the 0.012 m (0.5 inch) ceramic and 0.076 m (3 inch) plastic saddles. However, the 0.051 m (2 inch) Tri-Pack packing appeared to be more economical than the 0.025 m (1 inch) plastic saddles. The economical evaluation was limited in scope and only conducted at one air pressure drop gradient.

The Onda correlation predicted mass transfer coefficients that were similar to the 0.30 m (12 inch) column. Thus, using the Onda correlation to design a full scale system will produce a conservative design.

Credits:

The author expresses special thanks to Harold Wallman, Tom Kalinosky, Nathan L. Jacobson, and the employees of the Village of Brewster, NY in the design, construction, and operation of the 6, 12 and 57 inch packed column air stripping systems. The author also expresses special thanks to Eric Bissonette and Robert Kneipp in the construction and operation of the 24 inch packed column. Special thanks is also given to Brad Smith and H2M analytical laboratory in analysis of samples from this field evaluation. Finally, the author expresses special thanks to Dr. Thomas Love and Keith Carswell in overall project planning and guidance.

TABLE 1
Sample Port Location

Sample Port ID	Column Diameter (inch)			
	6	12	24	57
	Sample port height (ft)			
In	18.	18.	18.	17.7
A	15.75	17.	17.5	15.6
B	13.5	15.	15.5	13.4
C	11.25	13.	13.5	11.2
D	9.	11.	11.5	9.0
E	6.75	9.	9.5	6.8
F	4.5	7.	6.5	4.6
G	2.25	5.	4.5	2.4
H	None	3.	2.5	None
I	None	1.	0.5	None
Out	0.	0.	0.	0.

TABLE 2
Operating Data from Brewster, NY

Data Group	Analysis Number	Packing Size (inch)	Column Size (inch)	Air Water Ratio	Loading Air (m ³ m ⁻² sec ⁻¹)	Water (sec ⁻¹)	Field Run Number
1	1	0.5	6	51.	0.17	0.0034	13
	2	0.5	6	34.	0.16	0.0046	9
	3	0.5	6	20.	0.13	0.0067	8
	4	0.5	6	10.	0.10	0.0098	7
	5	0.5	6	5.0	0.067	0.014	6
	6	0.5	6	5.0	0.067	0.013	12
	7	0.5	6	49.	0.17	0.0035	10
2	8	1.	6	50.	0.44	0.0089	46
	9	1.	6	36.	0.40	0.011	45
	10	1.	6	21.	0.33	0.016	44
	11	1.	6	9.8	0.25	0.026	48
	12	1.	6	5.0	0.15	0.031	47
3	13	1.	12	50.	0.44	0.0088	43
	14	1.	12	36.	0.39	0.011	42
	15	1.	12	21.	0.33	0.016	41
	16	1.	12	9.9	0.25	0.026	40
	17	1.	12	5.0	0.15	0.031	39
4	18	1.	24	49.	0.44	0.0089	35
	19	1.	24	36.	0.39	0.011	34
	20	1.	24	20.	0.32	0.017	33
	21	1.	24	10.	0.26	0.026	32
	22	1.	24	5.0	0.15	0.030	31
5	23	1.	57	53.	0.47	0.0088	38
	24	1.	57	37.	0.40	0.011	37
	25	1.	57	22.	0.34	0.016	36
6	26	2.	6	47.	0.65	0.014	18
	27	2.	6	35.	0.61	0.017	20
	28	2.	6	20.	0.51	0.025	22
	29	2.	6	9.9	0.39	0.039	24
	30	2.	6	5.1	0.26	0.051	26
7	31	2.	12	51.	0.66	0.013	17
	32	2.	12	34.	0.61	0.018	19
	33	2.	12	20.	0.51	0.026	21
	34	2.	12	10.	0.39	0.039	23
	35	2.	12	5.0	0.25	0.051	25
8	36	2.	24	49.	0.66	0.014	30
	37	2.	24	36.	0.61	0.017	29
	38	2.	24	19.	0.50	0.026	28
	39	2.	24	9.9	0.39	0.039	27
9	40	3.	12	48.	0.66	0.014	2
	41	3.	12	35.	0.61	0.017	4
	42	3.	12	20.	0.51	0.026	5
	43	3.	12	48.	0.65	0.014	15
	44	3.	12	37.	0.60	0.016	16
10	45	3.	57	49.	0.66	0.014	14
	46	3.	57	36.	0.61	0.017	3
	47	3.	57	20.	0.51	0.025	11

TABLE 3
Brewster Tetrachloroethylene Data Set

Group #	Anal #	In	A	B	C	Sample Port				H	I	Out
						D	E	F	G			
Concentration (ug L ⁻¹)												
1	1	83.	48.	5.7	0.8							
	2	46.	28.	7.4	2.6							
	3	46.	26.	6.9	3.8							
	4	49.	38.	16.	8.5	2.2	2.9	2.2	1.9			
	5	45.	42.	26.	16.	14.	10.	7.6	5.4			3.2
	6	74.	67.	46.	32.	25.	19.	15.	10.			4.9
	7	52.	17.		0.9							
2	8	200.		52.	41.	36.	30.	13.	8.5			2.8
	9	200.	74.	64.	58.	55.	38.	21.	12.			5.2
	10	200.	110.	71.	69.	60.	41.	27.	21.			9.4
	11	180.	120.	120.	82.	75.	58.	46.	33.			21.
	12	190.	130.	130.	110.	100.	92.	75.	60.			39.
3	13	110.	85.		39.	22.	21.	9.1	2.7	1.8		1.6
	14	110.	94.	54.	21.	13.	8.2	4.1	1.3	1.0		0.7
	15	130.	96.	73.	56.	33.	31.	23.	6.9	4.8		4.1
	16	130.	110.	92.	82.	47.	38.	21.	8.7	7.8		7.0
	17	130.	120.	100.	96.	66.	59.	50.	27.	25.		11.
4	18	110.	100.	49.	29.	17.	9.1	2.8	1.7	0.8		
	19	95.	92.	37.	25.	13.	6.5	2.2	1.6	0.8	0.6	
	20	95.	77.	49.	30.	22.	14.	8.0	4.3	2.4	1.0	
	21	96.	86.	50.	33.	26.	15.	11.		5.7	4.6	
	22	83.	44.	67.	43.	47.	38.	32.	19.	15.	11.	
5	23	140.	39.	14.	7.4	2.0	1.5	1.3	0.9			0.8
	24	140.	36.	14.	5.6	2.9	2.8	1.4	0.9			0.8
	25	94.	20.	7.7	5.1	3.1	2.9	2.1	1.5			1.2
6	26	200.	120.	65.	61.	32.	18.	13.	7.3			4.1
	27	190.	130.	78.	67.	39.	26.	16.	9.7			4.7
	28	200.	140.	90.	80.	53.	34.	23.	18.			10.
	29	210.	150.	110.	92.	64.	55.	39.	35.			23.
	30	200.	160.	120.	120.	93.	85.	85.	59.			41.
7	31	77.	60.		23.	19.	14.	8.8	3.6	2.1		1.4
	32	99.	59.		34.		19.	12.	4.4	1.9		2.2
	33	93.	33.			37.	29.	15.	6.5	3.9		4.8
	34	93.	86.		51.	36.	40.	32.	13.	9.8		10.
	35	120.	96.		85.	74.	78.	56.	45.	35.		35.
8	36	59.	78.	37.	18.	2.2	1.8	0.9	2.9	2.3	2.6	
	37	88.	46.	50.	21.	12.	14.	8.4	1.8	2.1	2.3	
	38	68.	49.	33.	16.	14.	22.	18.	6.9	5.4	6.0	
	39	64.	69.	38.	39.	37.	34.	34.	24.	22.	21.	
9	40	26.	15.	15.		10.	5.5	5.3	3.6	2.4		1.8
	41	26.	13.	6.4		11.	7.6	5.6	4.5	2.9		
	42	24.	21.	18.		12.	7.4	9.6	7.0	5.0		4.3
	43	160.	43.	44.		33.	44.	23.	19.	11.	11.	
	44	97.	70.	43.		45.	51.	39.	26.	16.	16.	
10	45	72.	31.	20.	14.	13.	8.8	5.5	4.2			1.6
	46	24.	16.	8.4	7.5	6.3	4.0	2.9	1.9			0.8
	47	40.	31.	19.	11.	11.	11.	5.4	3.8			1.5

TABLE 4
Brewster Trichloroethylene Data Set

Group #	Anal #	Sample Port											Out
		In	A	B	C	D	E	F	G	H	I		
		Concentration (ug L ⁻¹)											
1	1	15.	6.2	0.8									
	2	7.4	6.9	5.4	2.2								
	3	7.0	4.5	2.2	1.8								
	4	7.3	6.5	4.0	2.9	2.3	1.8						
	5	6.9	6.6	5.8	5.0	4.9	4.5	3.7	3.1			2.2	
	6	12.	12.	11.	9.4	8.8	8.0	6.6	5.1			2.4	
	7	7.3	3.0										
2	8	28.		7.3	5.3	4.9	3.5	1.3	0.6			0.1	
	9	29.	12.	8.9	7.8	7.4	4.7	2.4	1.2			0.3	
	10	27.	15.	11.	10.	9.0	6.1	3.7	2.8			1.0	
	11	26.	18.	18.	14.	13.	11.	9.7	6.0			4.7	
	12	26.	20.	21.	19.	18.	17.	15.	13.			8.6	
3	13	28.	17.		7.0	3.2	2.9	1.5	0.4	0.3		0.2	
	14	25.	19.	10.	3.2	1.6	1.2	0.9					
	15	25.	18.	13.	11.	7.7	6.9	5.0	1.7	1.1		0.7	
	16	28.	24.	20.	17.	12.	7.5	6.0	3.0	2.2		1.8	
	17	28.	27.	22.	20.	16.	14.	12.	7.6	7.5		4.2	
4	18	22.	18.	8.0	4.6	2.6	1.4	0.5					
	19	18.	21.	6.7	5.3	2.6	1.4	0.5					
	20	24.	17.	13.	6.2	5.2	3.1	2.1	1.3	0.7			
	21	21.	20.	12.	8.6	7.8	4.3	3.5		1.7	1.3		
	22	18.	14.	14.	13.	12.	9.3	10.	5.5	4.5	4.4		
5	23	27.	7.6	2.4	1.0								
	24	28.	6.5	2.7	0.9	0.5							
	25	15.	3.9	1.6	1.0	0.6	0.5						
6	26	28.	17.	9.7	8.2	4.7	3.0	2.4	1.7			1.3	
	27	26.	18.	12.	10.	6.1	4.2	2.9	2.1			1.4	
	28	29.	22.	14.	13.	8.8	6.2	4.3	3.6			2.4	
	29	30.	24.	17.	15.	12.	9.8	7.5	6.9			4.8	
	30	28.	23.	20.	19.	17.	16.	12.	12.			8.2	
7	31	16.	13.		5.3	4.3	2.9	1.8	0.8				
	32	26.	13.		8.2		4.4	2.7	1.0	0.5		0.4	
	33	21.	12.			9.0	7.0	4.1	2.0	1.0		1.2	
	34	25.	26.		12.	10.	11.	8.3	3.8	3.3		2.9	
	35	25.	27.		22.	20.	19.	15.	12.	9.9		10.	
8	36	14.	11.	7.7	3.6	0.7	0.8	0.5	0.6	0.5	0.5		
	37	17.	11.	10.	4.4	2.5	3.3	2.0	0.7	0.8	0.6		
	38	12.	8.9	6.2	3.7	3.4	5.4	4.6	1.6	1.4	1.3		
	39	10.	11.	7.2	6.2	7.0	6.6	5.6	4.8	4.2	4.0		
9	40	4.0	2.1	2.2		1.6	0.9	0.8	0.7	0.4		0.4	
	41	4.0	1.9	1.0		2.0	1.2	1.1	0.8	0.6			
	42	3.9	3.7	3.0		2.0	1.2	1.5	1.1	0.8		0.7	
	43	22.	6.5	7.4		4.7	6.1	3.1	2.2	1.1		1.0	
	44	24.	15.	6.7		6.9	7.8	5.6	3.9	2.6		2.5	
10	45	13.	7.1	4.3	3.2	2.9	1.7	1.2	1.0				
	46	3.5	3.0	1.5	1.3	1.0	0.8	0.6	0.6			0.2	
	47	7.0	4.6	2.2	1.7	1.8	1.7	0.7	0.4				

TABLE 5
Brewster cis-1,2-Dichloroethylene Data Set

Brewster cis-1,2-Dichloroethylene Data Set													
Group #	Anal #	Sample Port										I	Out
		In	A	B	C	D	E	F	G	H			
Concentration (ug L ⁻¹)													
1	1	25.	11.	1.3									
	2	11.	8.9	4.5									
	3	11.	8.7	5.4	3.9	3.0							
	4	12.	12.	11.	9.9	8.8	7.2	6.6	5.1			3.3	
	5	12.	11.	11.		10.	10.	9.7	9.3			6.7	
	6	18.	19.	18.	17.	18.	18.	21.	18.			13.	
	7	12.	5.0										
2	8	53.		17.	13.	12.	8.9	4.5	2.2			0.5	
	9	56.	28.	20.	19.	17.	12.	7.1	3.5			1.6	
	10	51.	34.	29.	27.	24.	20.	13.	10.			5.2	
	11	54.	46.	48.	45.	43.	41.	36.	27.			21.	
	12	50.	44.	48.	44.	45.	45.	44.	43.			35.	
3	13	60.	41.		18.	11.	9.4	5.4	1.4	0.9		0.8	
	14	47.	39.	24.	9.4	6.1	4.9	3.8	1.1	1.0		0.5	
	15	59.	53.	40.	38.	30.	28.	23.	8.5	6.3		4.2	
	16	64.	63.	57.	43.	41.	34.	27.	16.	14.		13.	
	17	54.	51.	48.	50.	47.	46.	44.	36.	34.		25.	
4	18	57.	39.	23.	13.	9.9	5.4	2.3	1.7	0.7	0.5		
	19	44.	65.	29.	26.	17.	8.2	4.2	3.0	1.5	0.8		
	20	45.	39.	37.	22.	20.	18.	12.	9.4	5.4	1.6		
	21	40.	55.	53.	35.	34.	23.	28.		15.	10.		
	22	41.	19.	40.	37.	38.	33.	33.	25.	30.	20.		
5	23	68.	24.	9.3	3.2	1.4	0.7	1.1	0.8			0.6	
	24	62.	25.	10.	4.0	2.1	1.2	1.0	0.5			0.5	
	25	43.	16.	7.3	4.3	3.0	2.8	2.6	2.0			1.9	
6	26	53.	33.	24.	18.	10.	6.1	4.5	2.2			1.5	
	27	50.	37.	27.	24.	16.	11.	6.8	4.6			2.3	
	28	55.	45.	32.	34.	25.	19.	13.	12.			6.8	
	29	56.	48.	44.	40.	38.	32.	27.	24.			18.	
	30	53.	49.	44.	46.	42.	45.	41.	39.			27.	
7	31	41.	28.		12.	9.7	6.8	5.7	1.8	0.8		0.6	
	32	63.	29.		20.		11.	8.0	2.9	1.3		1.5	
	33	35.	25.			28.	24.	14.	8.5	5.9		4.6	
	34	49.	37.		35.	32.	32.	31.	18.	17.		14.	
	35	42.	59.		55.	55.	44.	42.	35.	30.		37.	
8	36	25.	35.	22.	10.	2.9	3.3	2.0	2.5	2.1	2.4		
	37	32.	28.	27.	15.	9.5	11.	8.9	3.0	3.3	3.0		
	38	32.	27.	21.	23.	13.	16.	14.	6.4	6.0	4.3		
	39	45.	48.	30.	33.	29.	33.	30.	17.	19.	18.		
9	40	7.7	4.7	4.8		3.8	2.1	1.9	1.3	0.6		0.8	
	41	7.6	4.2	2.6		4.6	3.3	2.5	1.4	1.2			
	42	7.6	7.2	6.7		4.8	3.7	4.2	2.7	2.3		1.6	
	43	43.	18.	19.		12.	13.	8.2	4.9	2.7		2.5	
	44	43.	33.	20.		18.	18.	13.	10.	6.1		5.7	
10	45	33.	13.	8.4	6.9	6.8	4.2	3.0	2.0			0.5	
	46	6.6	5.3	3.2	2.4	2.5	1.7	1.2	1.1			0.3	
	47	17.	14.	9.2	7.2	7.1	5.3	3.9	2.8			0.9	

TABLE 6

Comparison of X_u , $K_L a$, and Fraction Remaining
Using Overall best fit Henry's Coefficient
Tetrachloroethylene

Column Size (in)	Packing Size (in)	Henry's Coeff. (atm)	x_u	KLa (sec ⁻¹) Air to Water Ratio					Fraction Remaining Air to Water Ratio				
				50	35	20	10	5	50	35	20	10	5
6	0.5	0.30	0.0	0.0085	0.0075	0.0094	0.010	0.013	0.0000	0.0003	0.0014	0.015	0.069
6	1.	0.30	0.0	0.0064	0.0065	0.0086	0.012	0.011	0.023	0.048	0.073	0.13	0.26
12	1.	0.30	0.0	0.0078	0.012	0.012	0.021	0.025	0.0097	0.0040	0.026	0.035	0.087
24	1.	0.30	0.0	0.0099	0.012	0.015	0.020	0.017	0.0032	0.0043	0.013	0.042	0.16
57	1.	0.30	0.012	0.014	0.017	0.035			0.012	0.012	0.012		
6	2.	0.30	0.0	0.010	0.012	0.015	0.019	0.019	0.023	0.028	0.053	0.12	0.25
12	2.	0.30	0.0	0.010	0.014	0.016	0.022	0.018	0.017	0.018	0.052	0.085	0.28
24	2.	0.30	0.017	0.028	0.016	0.013	0.0093		0.017	0.026	0.099	0.34	
12	3.	0.30	0.0	0.0066	0.0064	0.0091			0.079	0.15	0.17		
57	3.	0.30	0.0	0.0086	0.010	0.015			0.039	0.047	0.052		

TABLE 7

Comparison of X_u , $K_L a$, and Fraction Remaining
Using Overall best fit Henry's Coefficient
Trichloroethylene

Column Size (in)	Packing Size (in)	Henry's Coeff. (atm)	X_u	KLa (sec ⁻¹) Air to Water Ratio				Fraction Remaining Air to Water Ratio					
				50	35	20	10	5	50	35	20	10	5
6	0.5	0.21	0.0	0.0080	0.0030	0.0061	0.0071	0.0048	0.0000	0.040	0.017	0.069	0.33
6	1.	0.21	0.0	0.0087	0.0085	0.0099	0.010	0.0088	0.0072	0.022	0.058	0.20	0.39
12	1.	0.21	0.0	0.0089	0.013	0.013	0.022	0.029	0.0059	0.0025	0.028	0.048	0.15
24	1.	0.21	0.0	0.010	0.013	0.015	0.021	0.018	0.0028	0.0030	0.020	0.055	0.22
57	1.	0.21	0.025	0.021	0.025	0.036			0.025	0.025	0.025		
6	2.	0.21	0.0	0.0084	0.010	0.013	0.017	0.018	0.047	0.054	0.084	0.17	0.33
12	2.	0.21	0.0	0.010	0.015	0.017	0.024	0.018	0.020	0.015	0.049	0.094	0.33
24	2.	0.21	0.029	0.023	0.015	0.012	0.0084		0.029	0.042	0.13	0.40	
12	3.	0.21	0.0	0.0058	0.0054	0.0099			0.11	0.20	0.16		
57	3.	0.21	0.0	0.0078	0.0086	0.017			0.056	0.082	0.051		

TABLE 8

Comparison of X_u , $K_L a$, and Fraction Remaining
Using Overall best fit Henry's Coefficient
cis-1,2-Dichloroethylene

Column Size (in)	Packing Size (in)	Henry's Coeff. (atm)	X _u	KLa (sec ⁻¹) Air to Water Ratio				Fraction Remaining Air to Water Ratio					
				50	35	20	10	5	50	35	20	10	5
6	0.5	0.094	0.0	0.0092	0.0044	0.0067	0.0050	0.0082	0.0000	0.018	0.039	0.27	0.54
6	1.	0.094	0.0	0.0079	0.0079	0.0085	0.0073	0.0017	0.017	0.044	0.13	0.41	0.80
12	1.	0.094	0.0	0.0089	0.012	0.013	0.022	0.013	0.0097	0.0092	0.064	0.20	0.54
24	1.	0.094	0.0	0.0094	0.011	0.015	0.024	0.032	0.0083	0.013	0.051	0.19	0.53
57	1.	0.094	0.010	0.019	0.020	0.014			0.0097	0.010	0.056		
6	2.	0.094	0.0	0.011	0.012	0.013	0.014	0.037	0.027	0.050	0.14	0.35	0.52
12	2.	0.094	0.0	0.012	0.016	0.015	0.018	0.0092	0.014	0.022	0.12	0.30	0.63
24	2.	0.094	0.053	0.023	0.013	0.017	0.014		0.054	0.085	0.15	0.38	
12	3.	0.094	0.0	0.0069	0.0065	0.010			0.091	0.18	0.21		
57	3.	0.094	0.0	0.010	0.010	0.019			0.034	0.071	0.074		

TABLE 9
Packed Column Air Stripping Design Using Pilot Data

Group	Test	Packing	Pilot	Air	Water	Loading	Pilot	Full Scale	Air	Capital	Operating	Production
θ	θ	Size	Column	Ratio	Ratio	$(m^3 m^{-2} sec^{-1})$	Kla	Diameter	Height	Pressure	(K\$ year ⁻¹)	(c per 1000 gal)
		(inch)	(inch)				$(sec^{-1})[(m^{-2} m^{-1})]$	(inch)	(ft)	(inch H ₂ O)	(K\$)	
1	1	0.5	6	51.	0.17	0.0034	0.0085	110.	7.7	2400.	2.3	16.
	2	0.5	6	34.	0.16	0.0046	0.0075	97.	12.	1600.	2.5	16.
	3	0.5	6	20.	0.13	0.0067	0.0094	80.	15.	910.	2.6	16.
	4	0.5	6	10.	0.10	0.0098	0.010	66.	26.	470.	3.0	18.
	5	0.5	6	5.0	0.067	0.014	0.013	57.	66.	230.	4.5	30.
	6	0.5	6	5.0	0.067	0.013	0.013	57.	65.	230.	4.4	30.
	7	0.5	6	49.	0.17	0.0035	0.0075	110.	9.1	2300.	2.3	18.
2	8	1.	6	50.	0.44	0.0089	0.0064	70.	27.	2300.	3.0	13.
	9	1.	6	36.	0.40	0.011	0.0065	63.	34.	1700.	3.2	13.
	10	1.	6	21.	0.33	0.016	0.0086	52.	40.	960.	3.4	12.
	11	1.	6	9.8	0.25	0.026	0.012	41.	60.	450.	4.4	13.
3	12	1.	6	5.0	0.15	0.031	0.011	38.	170.	230.	6.4	25.
	13	1.	12	50.	0.44	0.0088	0.0078	70.	22.	2300.	2.8	12.
	14	1.	12	36.	0.39	0.011	0.012	63.	18.	1700.	2.6	11.
	15	1.	12	21.	0.33	0.016	0.012	52.	28.	960.	3.0	10.
4	16	1.	12	9.8	0.25	0.026	0.011	41.	33.	460.	3.3	10.
	17	1.	12	5.0	0.15	0.031	0.011	37.	73.	230.	4.0	14.
	18	1.	24	49.	0.44	0.0089	0.0099	70.	17.	2300.	2.8	11.
	19	1.	24	36.	0.39	0.011	0.012	63.	18.	1700.	2.6	10.
5	20	1.	24	20.	0.32	0.017	0.015	51.	24.	910.	3.1	9.6
	21	1.	24	10.	0.26	0.026	0.020	45.	35.	460.	4.0	10.
	22	1.	24	5.0	0.15	0.030	0.017	38.	110.	230.	5.6	18.
	23	1.	57	53.	0.47	0.0088	0.014	70.	12.	2500.	2.5	9.2
6	24	1.	57	37.	0.40	0.011	0.017	63.	13.	1700.	2.4	8.8
	25	1.	57	22.	0.34	0.016	0.015	53.	9.6	1000.	2.3	7.4
	26	2.	6	47.	0.65	0.014	0.010	56.	27.	2200.	3.1	11.
	27	2.	6	35.	0.61	0.017	0.012	50.	28.	1600.	3.2	10.
7	28	2.	6	20.	0.51	0.025	0.015	42.	36.	940.	3.6	10.
	29	2.	6	9.8	0.39	0.039	0.019	33.	56.	460.	4.8	11.
	30	2.	6	5.1	0.26	0.051	0.019	29.	150.	240.	8.5	15.
	31	2.	12	51.	0.66	0.013	0.010	58.	25.	2400.	3.0	11.
8	32	2.	12	34.	0.61	0.018	0.014	50.	25.	1600.	3.1	10.
	33	2.	12	20.	0.51	0.026	0.016	41.	36.	910.	3.6	10.
	34	2.	12	10.	0.39	0.039	0.022	33.	47.	470.	4.3	10.
	35	2.	12	5.0	0.25	0.051	0.018	29.	180.	230.	9.5	22.
9	36	2.	24	49.	0.66	0.014	0.028	56.	9.5	2300.	2.4	7.9
	37	2.	24	36.	0.61	0.017	0.016	51.	21.	1700.	2.9	9.3
	38	2.	24	19.	0.50	0.026	0.013	41.	43.	900.	3.9	11.
	39	2.	24	9.9	0.39	0.039	0.019	33.	110.	460.	7.6	17.
10	40	3.	12	48.	0.66	0.014	0.0066	56.	40.	2300.	3.6	12.
	41	3.	12	35.	0.61	0.017	0.0064	50.	54.	1600.	4.3	13.
	42	3.	12	20.	0.51	0.026	0.0091	41.	62.	910.	4.8	13.
	43	3.	12	10.	0.39	0.039	0.0055	33.	56.	460.	7.6	13.
11	44	3.	12	37.	0.60	0.016	0.0052	51.	63.	1700.	4.5	15.
	45	3.	57	49.	0.66	0.014	0.0086	56.	31.	2300.	3.3	11.
	46	3.	57	36.	0.61	0.017	0.010	50.	33.	1700.	3.4	10.
	47	3.	57	20.	0.51	0.026	0.015	42.	35.	940.	3.5	9.6

TABLE 10
Example Calculation of Onda's Mass Transfer Coefficient Model

Temperature =	11.0	(Deg. C)
Inputs to Model:		
Liquid Loading =	0.016	(m ³ m ⁻² sec ⁻¹)
Air Loading =	0.32	(m ³ m ⁻² sec ⁻¹)
Acceleration of gravity =	9.80	(m sec ⁻²)
Gas Law Constant =	0.0821	(atm m ³ KM ⁻¹ Deg K ⁻¹)
Molar Volume of Gas at STP =	22.4	(m ³ KM ⁻¹)
Standard Temperature =	273.0	(Deg K)
Standard Pressure =	1.00	(atm)
Air at 11 Deg. C		
Molecular Weight =	28.95	(Kg KM ⁻¹)
Density =	1.24	(Kg m ⁻³)
Viscosity =	1.7E-5	(Kg m ⁻¹ sec ⁻¹)
Water at 11 Deg. C		
Molecular Weight =	18.0	(Kg KM ⁻¹)
Density =	998.	(Kg m ⁻³)
Viscosity =	0.0013	(Kg m ⁻¹ sec ⁻¹)
Surface Tension =	0.074	(Kg sec ⁻²)
Tetrachloroethylene at 11 Deg. C		
Molecular Weight =	165.8	(gm M ⁻¹)
Molecular Volume =	0.13	(m ³ KM ⁻¹)
Boiling Point =	394.4	(Deg. K)
Air Diffusion Coef. =	7.0E-6	(m ² sec ⁻¹)
Water Diffusion Coef =	5.7E-10	(m ² sec ⁻¹)
Henry's Coefficient =	0.30	(atm m ³ m ⁻³)
1 inch Plastic Glitsch Saddles:		
Nominal Size =	0.025	(m)
Surface Area =	200.	(m ² m ⁻³)
Surface Tension =	0.033	(Kg sec ⁻²)
Internals from Onda's Model:		
Reynolds Number =	62.	
Froude Number =	0.0054	
Weber Number =	0.017	
Wetted Area =	100.	(m ² m ⁻³)
Shape Factor =	5.2	
Liquid Phase:		
Reynolds Number =	120.	
Schmidt Number =	2300.	
Sherwood Number =	0.0052	
K _L =	0.00013	(m sec ⁻¹)
Air Phase:		
Reynolds Number =	120.	
Schmidt Number =	2.0	
Sherwood Number =	7.0	
K _g =	0.00044	(KM m ² sec ⁻¹ atm ⁻¹)
Overall K _{La} =	0.012	(sec ⁻¹)

TABLE 11

Mass Transfer Coefficient Estimated by the Onda Correlation
for Tetrachloroethylene
Henry's Coefficient=0.30

Pilot Column (in)	Packing Size (in)	Kla Estimated by Onda Correlation (sec ⁻¹)				
		Air to Water Ratio				
		50	35	20	10	5
6	0.5	0.0062	0.0077	0.010	0.013	0.015
6	1.	0.0079	0.0093	0.012	0.017	0.019
12	1.	0.0078	0.0092	0.012	0.017	0.019
24	1.	0.0078	0.0090	0.012	0.017	0.019
57	1.	0.0079	0.0091	0.012		
6	2.					
12	2.					
24	2.					
12	3.	0.0092	0.011	0.014		
57	3.	0.0092	0.011	0.014		

TABLE 12

Mass Transfer Coefficient Estimated by the Onda Correlation
for Trichloroethylene
Henry's Coefficient=0.21

Pilot Column (in)	Packing Size (in)	Kla Estimated by Onda Correlation (sec ⁻¹)				
		Air to Water Ratio				
		50	35	20	10	5
6	0.5	0.0064	0.0079	0.010	0.013	0.015
6	1.	0.0083	0.0097	0.013	0.018	0.019
12	1.	0.0082	0.0096	0.013	0.018	0.019
24	1.	0.0082	0.0094	0.013	0.018	0.019
57	1.	0.0082	0.0095	0.012		
6	2.					
12	2.					
24	2.					
12	3.	0.0094	0.011	0.014		
57	3.	0.0094	0.011	0.014		

TABLE 13

Mass Transfer Coefficient Estimated by the Onda Correlation
for cis-1,2-Dichloroethylene
Henry's Coefficient=0.094

Pilot Column (in)	Packing Size (in)	Kla Estimated by Onda Correlation (sec ⁻¹)				
		Air to Water Ratio				
		50	35	20	10	5
6	0.5	0.0061	0.0074	0.0092	0.011	0.012
6	1.	0.0085	0.0098	0.013	0.017	0.018
12	1.	0.0084	0.0098	0.013	0.017	0.018
24	1.	0.0084	0.0096	0.013	0.017	0.018
57	1.	0.0084	0.0097	0.012		
6	2.					
12	2.					
24	2.					
12	3.	0.0089	0.010	0.013		
57	3.	0.0089	0.010	0.012		

Figure 1

Packed Column Air Stripping Process

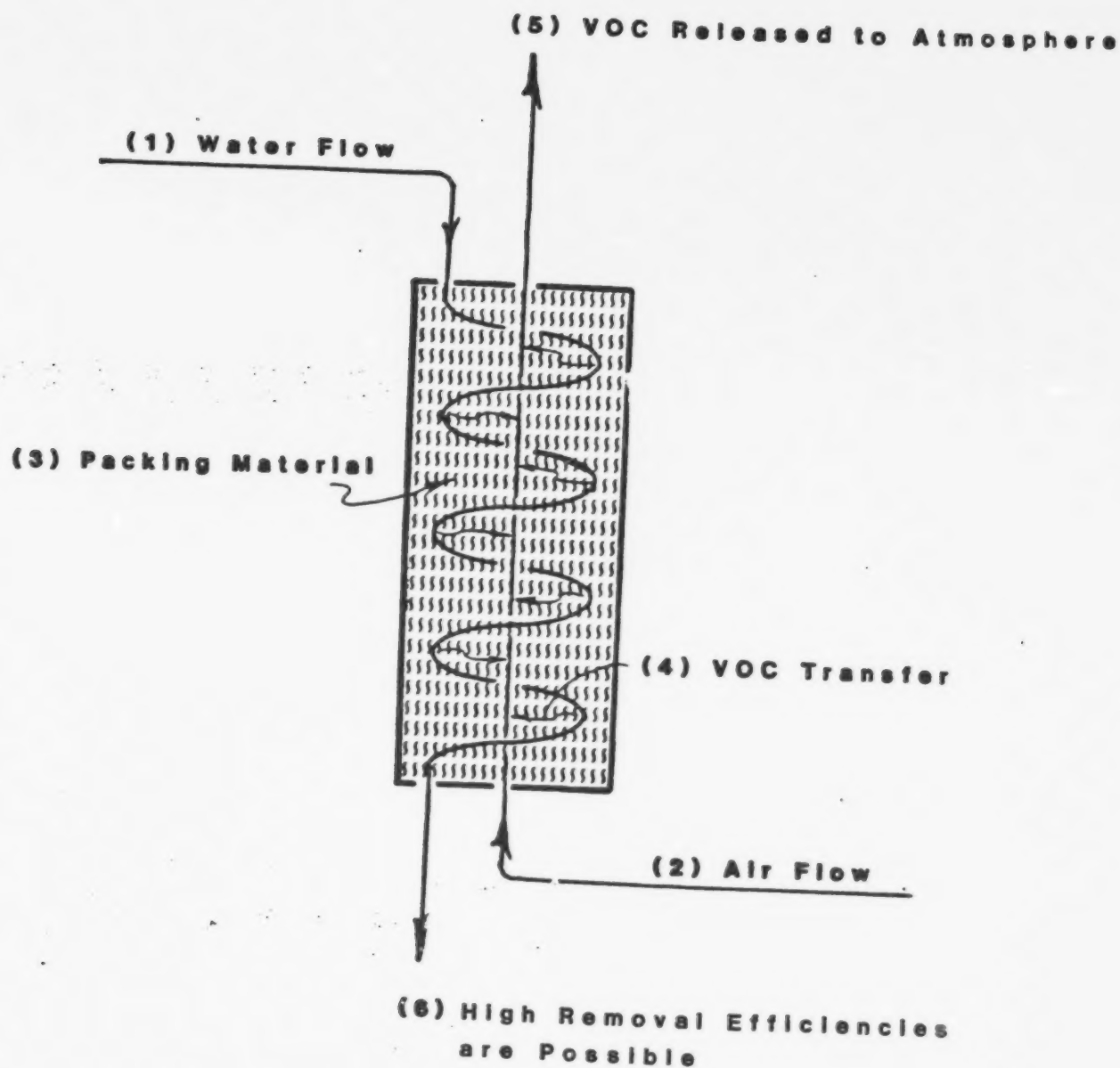


Figure 2
Air to Water Ratio

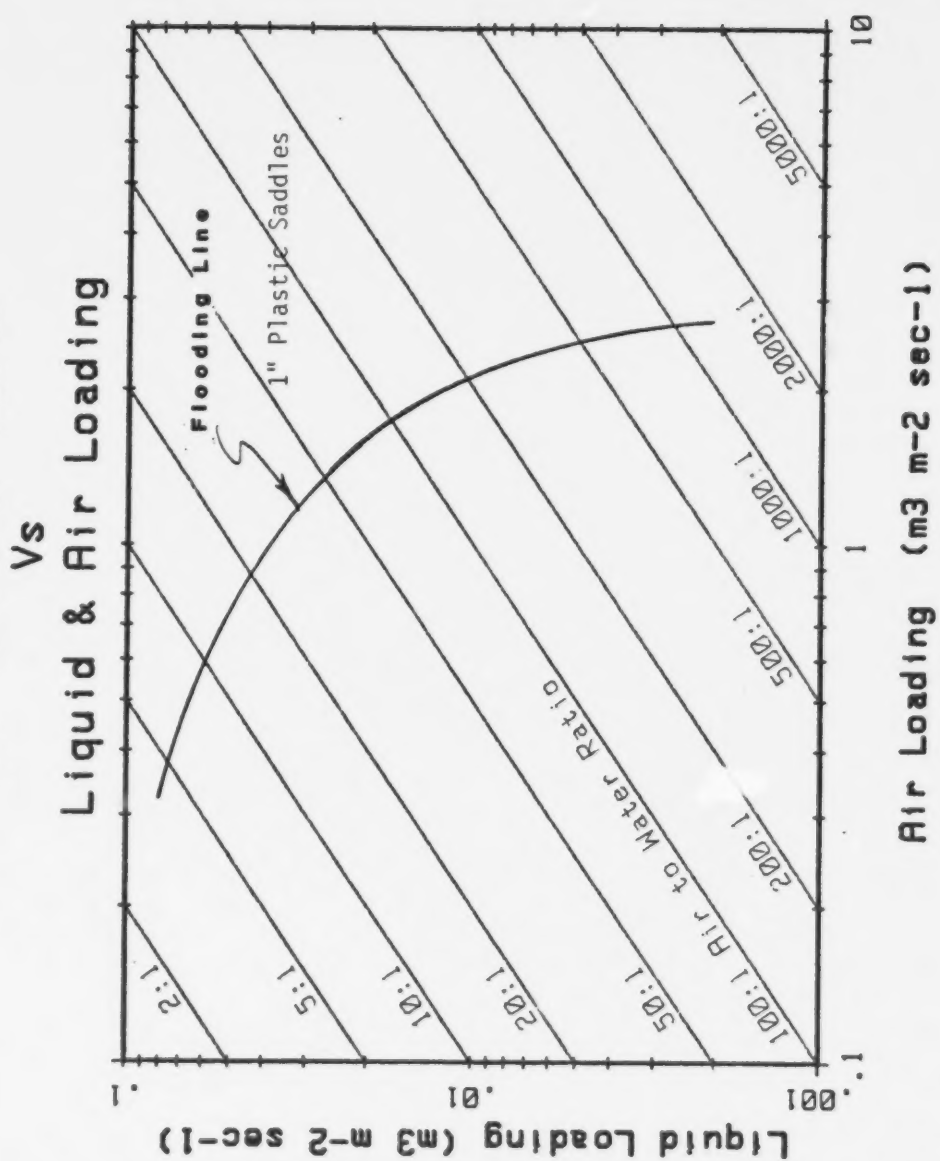


Figure 3

Packed Column Air Stripping Pilot System

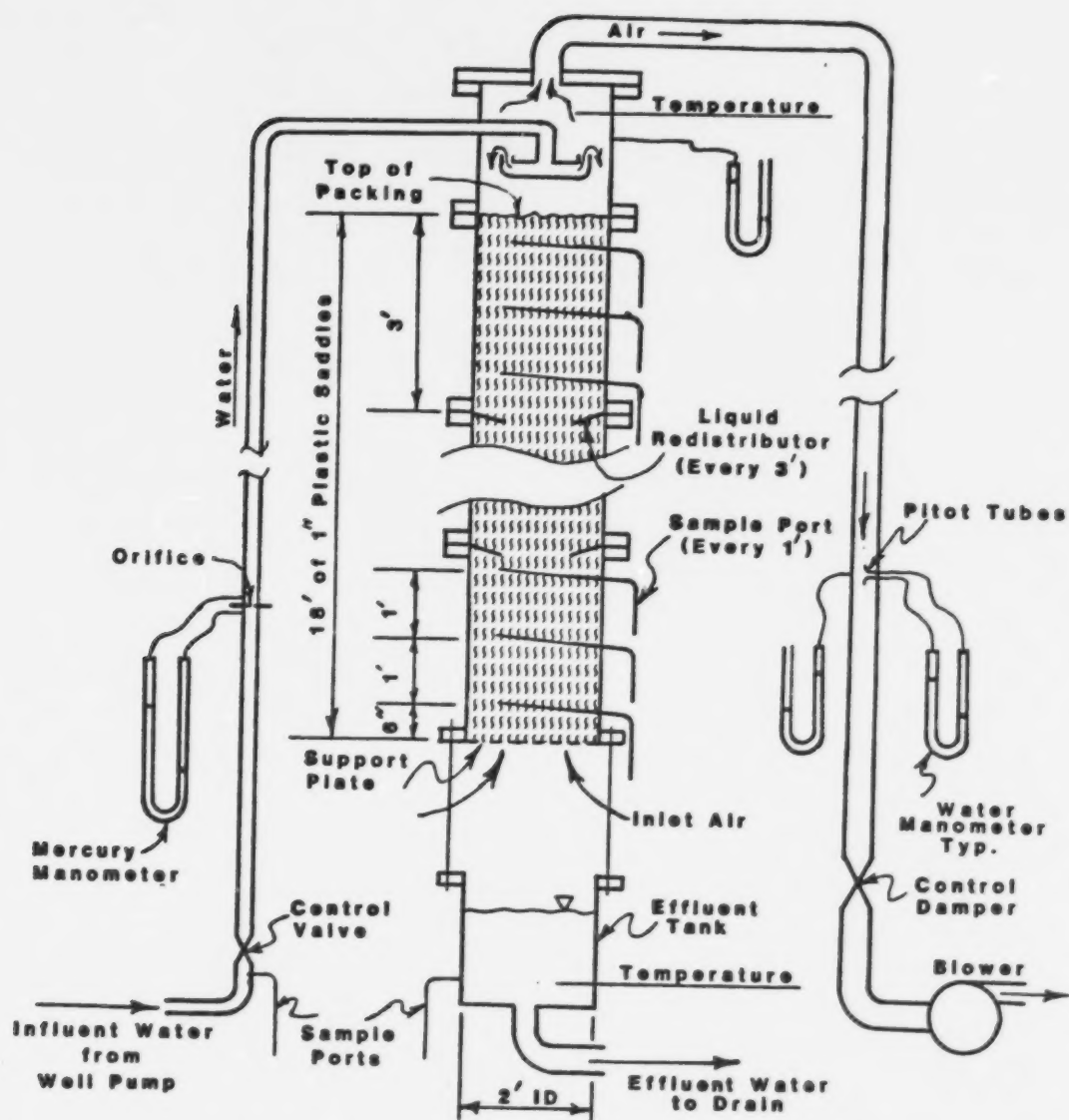
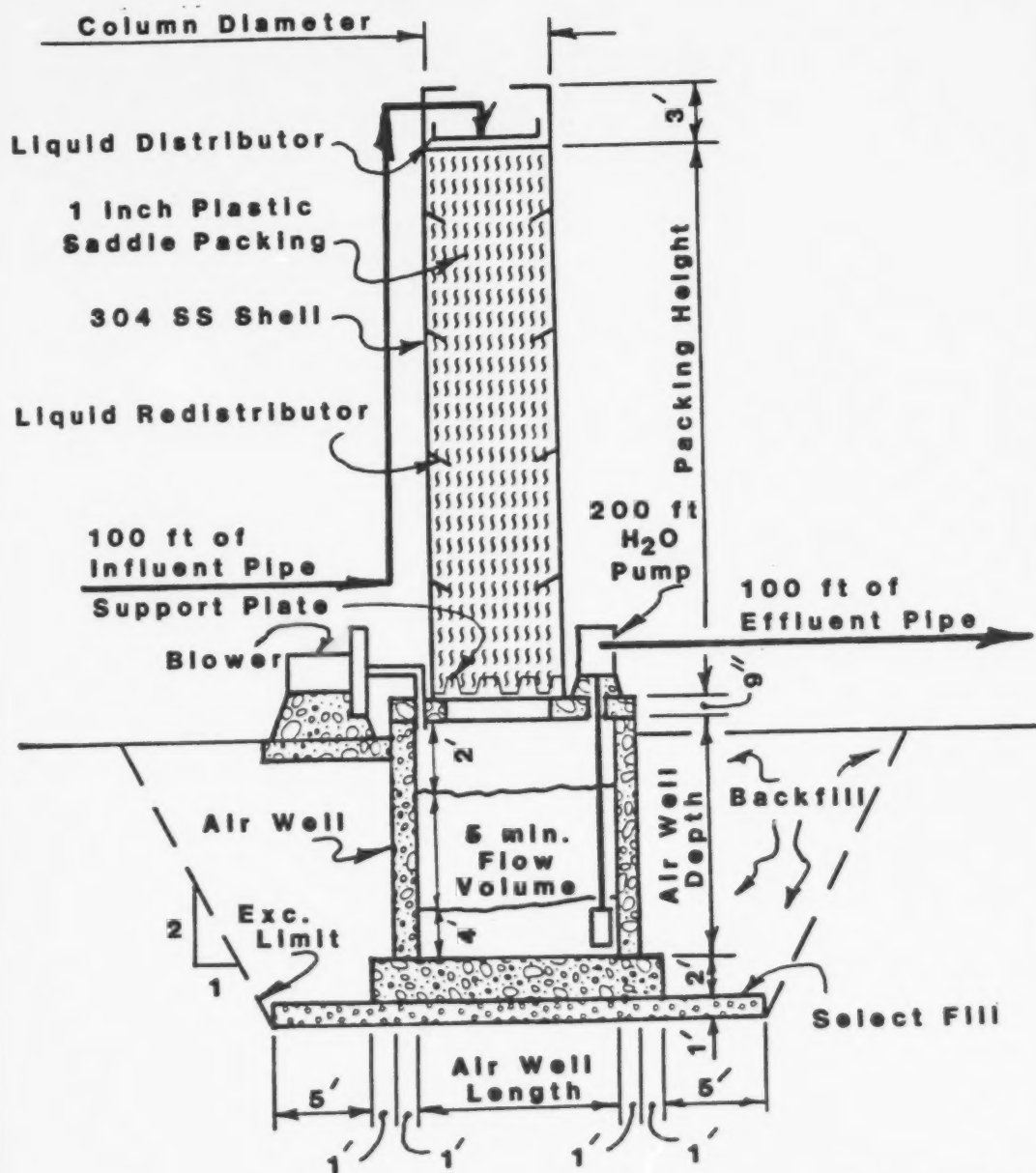


Figure 4
Cost Model Configuration

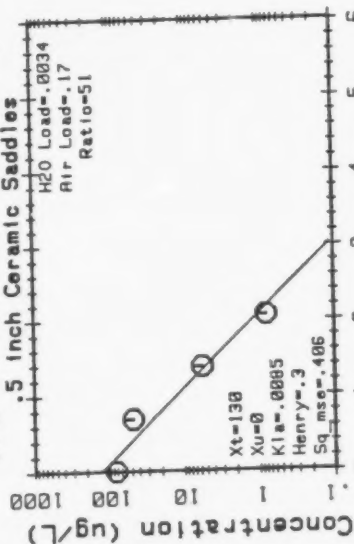


APPENDIX B

CONCENTRATION PROFILES FOR TETRACHLOROETHYLENE

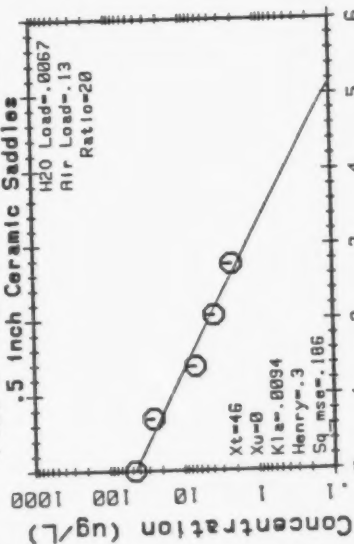
Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

Plot 1 - Run 13 - 6 inch Column
.5 inch Ceramic Saddles



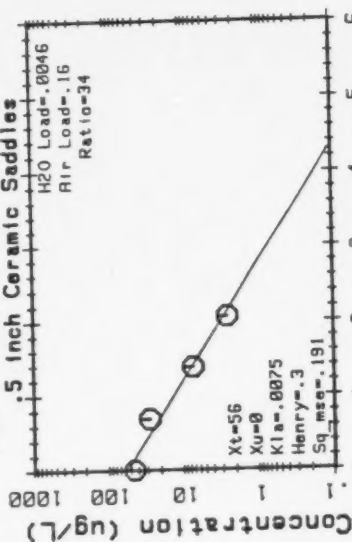
Location (Z) from Top of Packing (m)

Plot 3 - Run 8 - 6 inch Column
.5 inch Ceramic Saddles



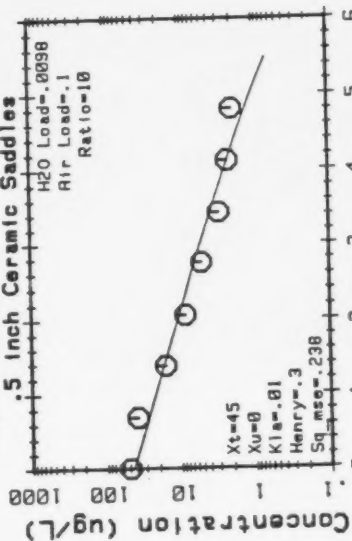
Location (Z) from Top of Packing (m)

Plot 2 - Run 9 - 6 inch Column
.5 inch Ceramic Saddles



Location (Z) from Top of Packing (m)

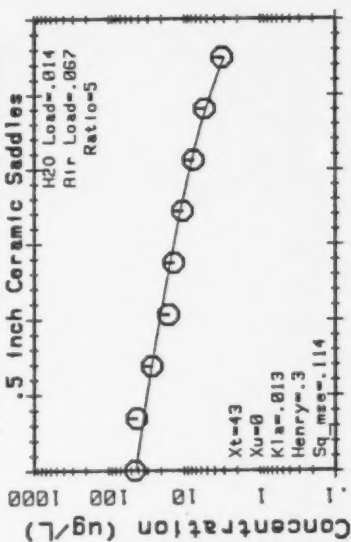
Plot 4 - Run 7 - 6 inch Column
.5 inch Ceramic Saddles



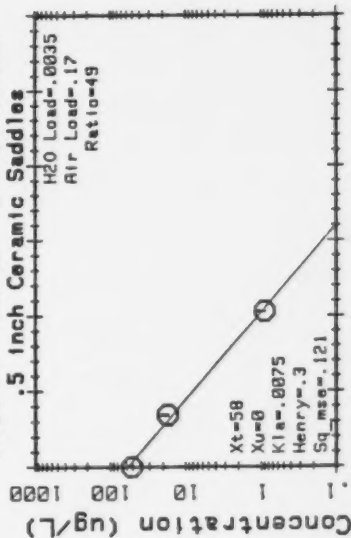
Location (Z) from Top of Packing (m)

Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

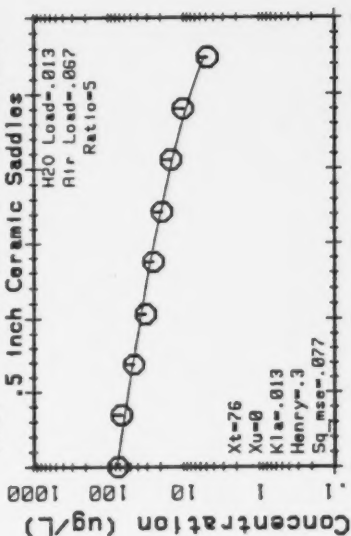
Plot 5 - Run 6 - 6 Inch Column
.5 inch Ceramic Saddles



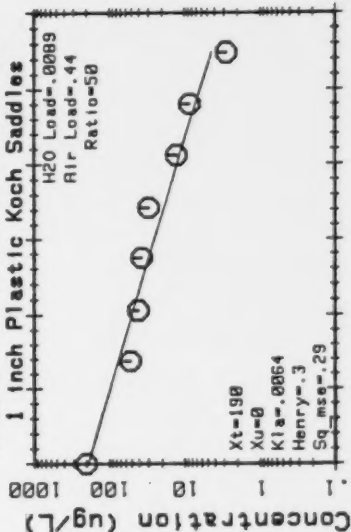
Plot 7 - Run 10 - 6 Inch Column
.5 inch Ceramic Saddles



Plot 6 - Run 12 - 6 Inch Column
.5 inch Ceramic Saddles

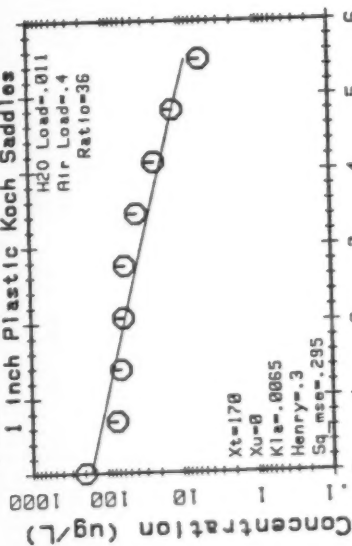


Plot 8 - Run 46 - 6 Inch Column
1 inch Plastic Koch Saddles



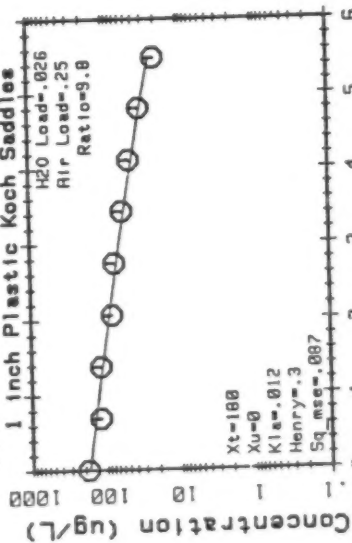
Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

Plot 9 - Run 45 - 6 inch Column
1 inch Plastic Koch Saddles



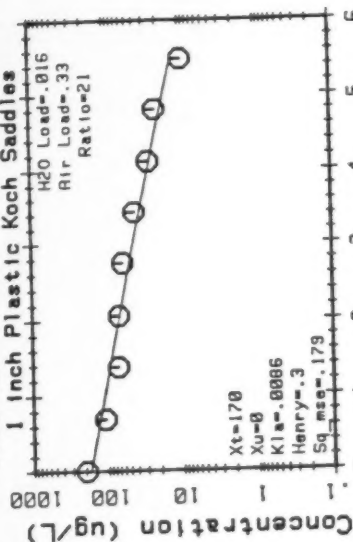
Location (Z) from Top of Packing (m)

Plot 11 - Run 48 - 6 inch Column
1 inch Plastic Koch Saddles



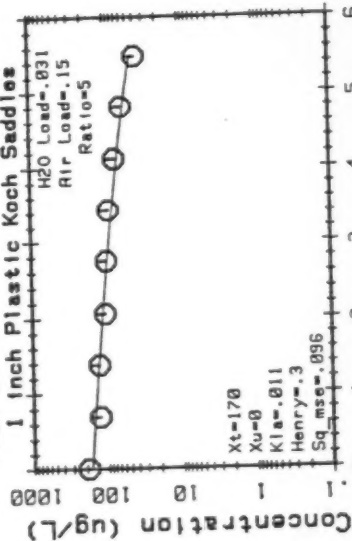
Location (Z) from Top of Packing (m)

Plot 10 - Run 44 - 6 inch Column
1 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

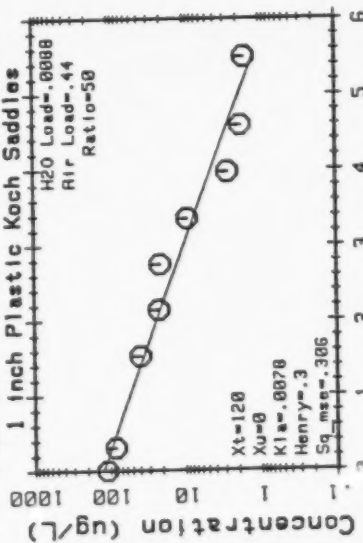
Plot 12 - Run 47 - 6 inch Column
1 inch Plastic Koch Saddles



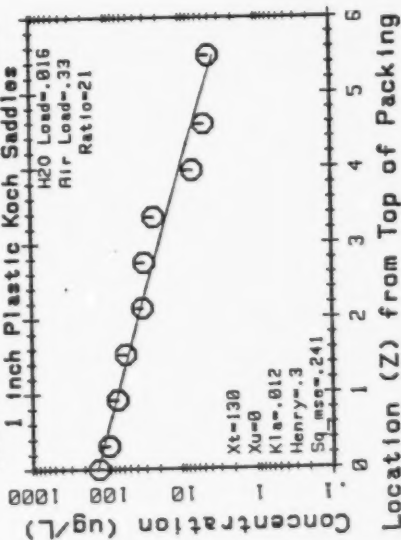
Location (Z) from Top of Packing (m)

Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

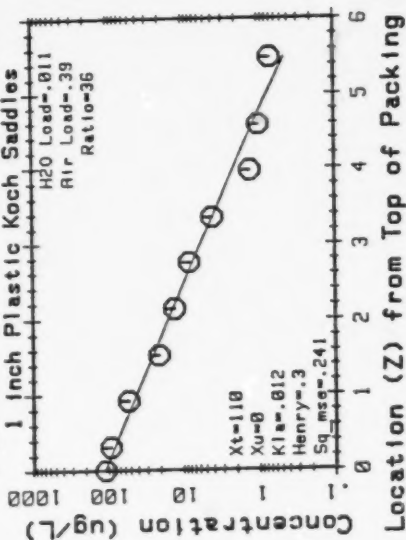
Plot 13 - Run 43 - 12 inch Column
1 inch Plastic Koch Saddles



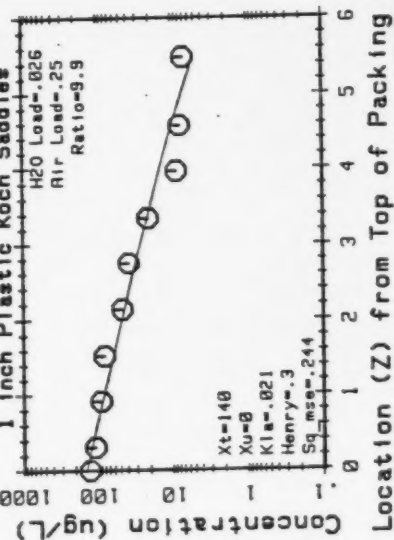
Plot 15 - Run 41 - 12 inch Column
1 inch Plastic Koch Saddles



Plot 14 - Run 42 - 12 inch Column
1 inch Plastic Koch Saddles

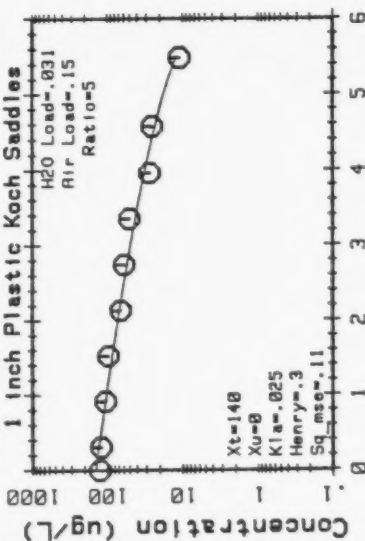


Plot 16 - Run 40 - 12 inch Column
1 inch Plastic Koch Saddles



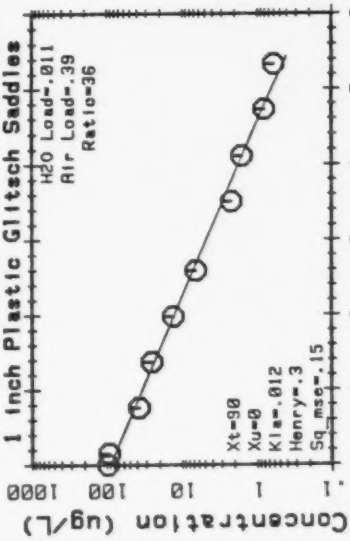
Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

Plot 17 - Run 39 - 12 inch Column
1 inch Plastic Koch Saddles



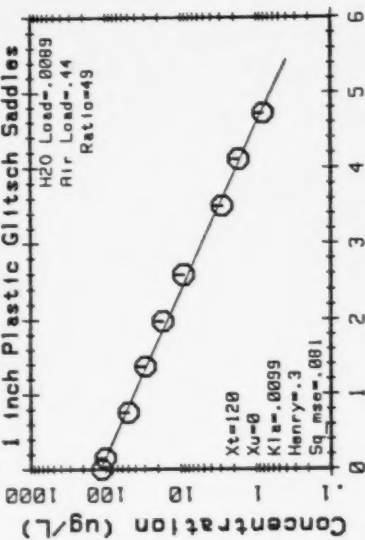
Location (Z) from Top of Packing (m)

Plot 19 - Run 34 - 24 inch Column
1 inch Plastic Glitsch Saddles



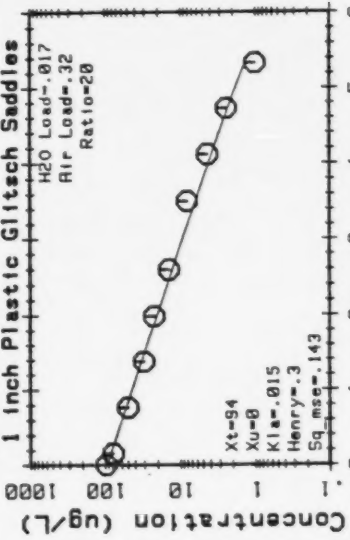
Location (Z) from Top of Packing (m)

Plot 18 - Run 35 - 24 inch Column
1 inch Plastic Glitsch Saddles



Location (Z) from Top of Packing (m)

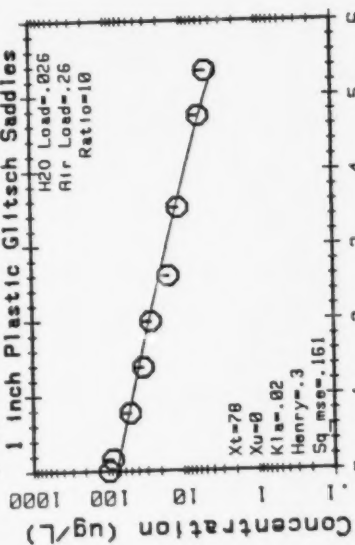
Plot 20 - Run 33 - 24 inch Column
1 inch Plastic Glitsch Saddles



Location (Z) from Top of Packing (m)

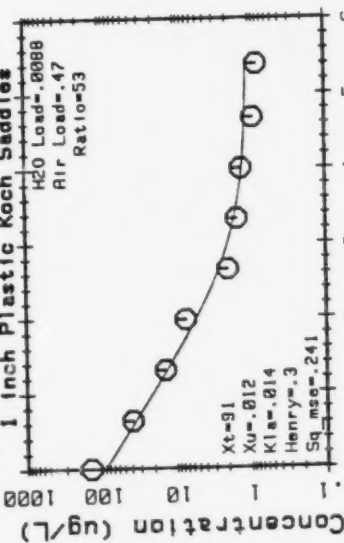
Packed Column Air Stripping Data
Brewster, NY - Tetrachloroethylene

Plot 21 - Run 32 - 24 inch Column
1 inch Plastic Glitsch Saddles



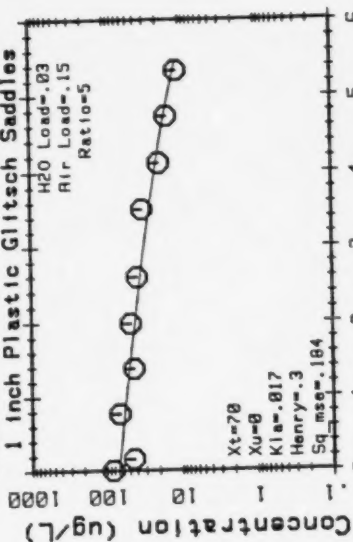
Location (Z) from Top of Packing (m)

Plot 23 - Run 38 - 57 inch Column
1 inch Plastic Koch Saddles



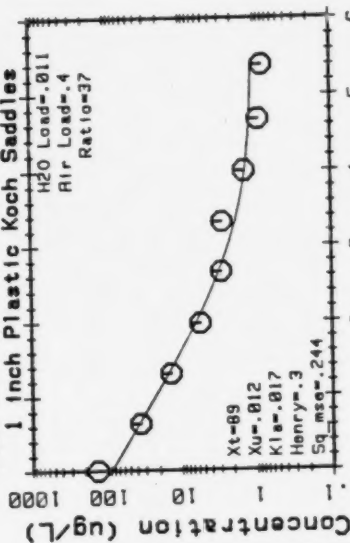
Location (Z) from Top of Packing (m)

Plot 22 - Run 31 - 24 inch Column
1 inch Plastic Glitsch Saddles



Location (Z) from Top of Packing (m)

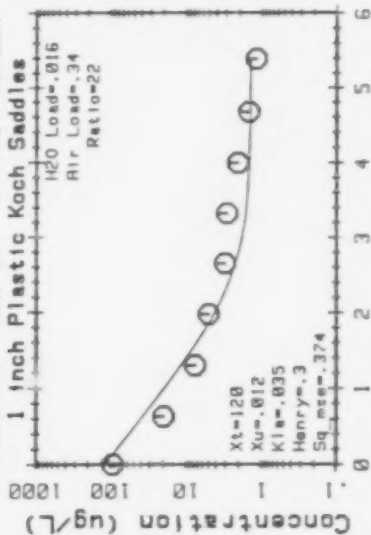
Plot 24 - Run 37 - 57 inch Column
1 inch Plastic Koch Saddles



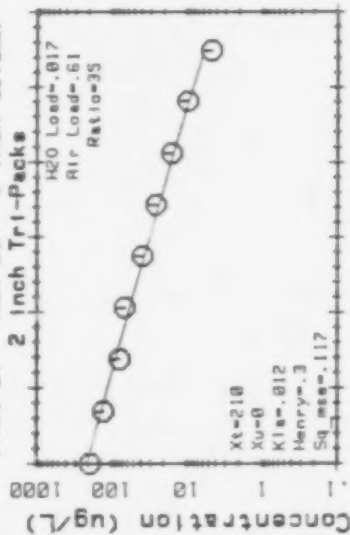
Location (Z) from Top of Packing (m)

Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

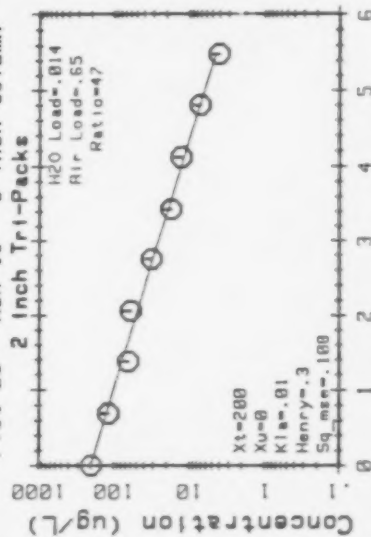
Plot 25 - Run 36 - 57 inch Column
1 inch Plastic Koch Saddles



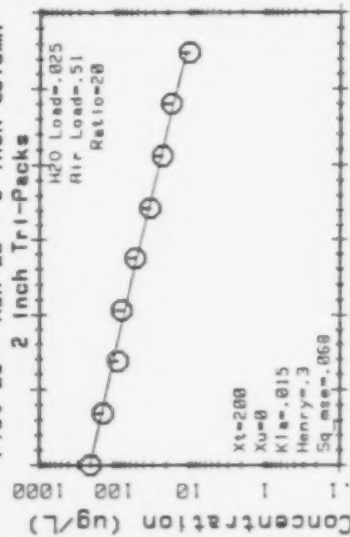
Plot 27 - Run 28 - 6 inch Column
2 inch Tri-Packs



Plot 26 - Run 18 - 6 inch Column
2 inch Tri-Packs



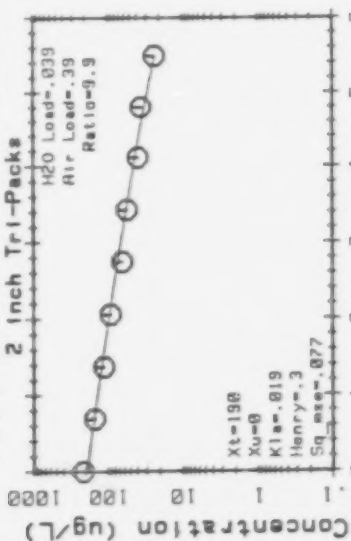
Plot 28 - Run 22 - 6 inch Column
2 inch Tri-Packs



Plot 25 - Run 36 - 57 inch Column
1 inch Plastic Koch Saddles

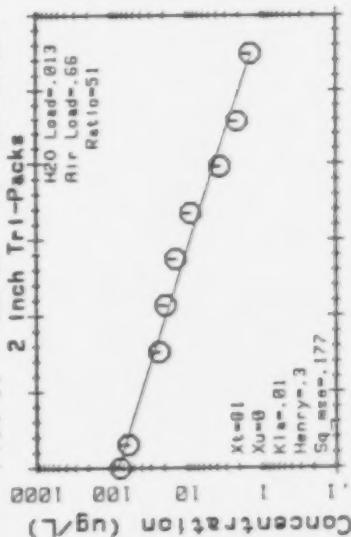
Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

Plot 29 - Run 24 - 6 inch Column
2 inch Tri-Packs



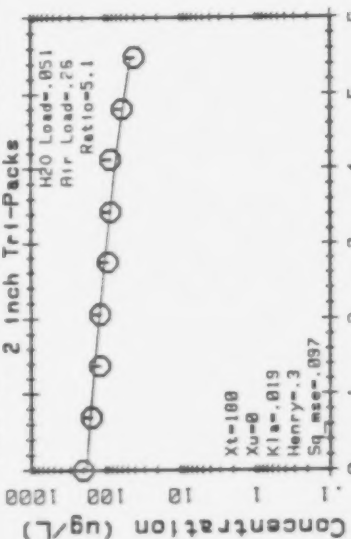
Location (Z) from Top of Packing (m)

Plot 31 - Run 17 - 12 inch Column
2 inch Tri-Packs



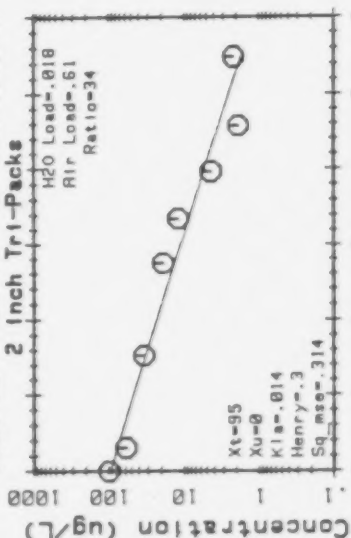
Location (Z) from Top of Packing (m)

Plot 30 - Run 26 - 6 inch Column
2 inch Tri-Packs



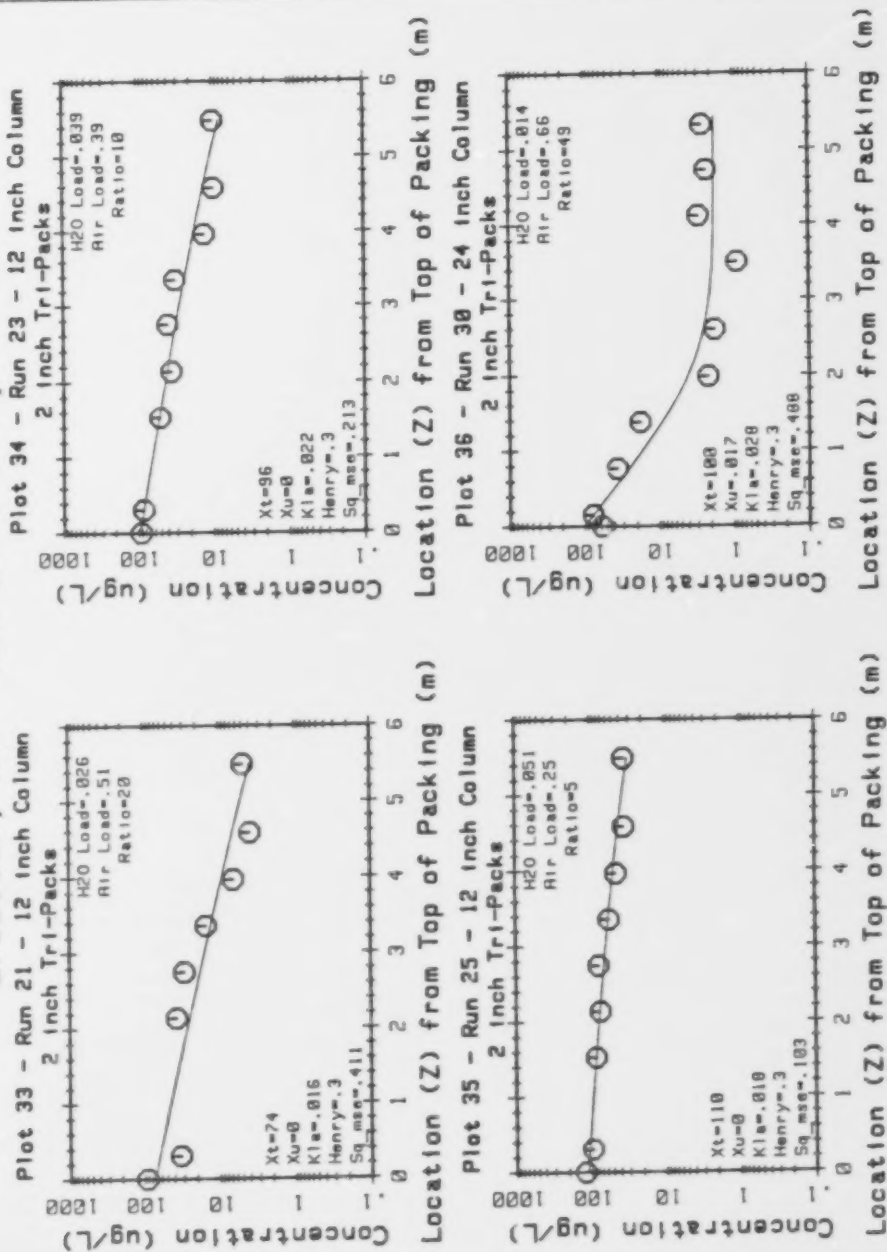
Location (Z) from Top of Packing (m)

Plot 32 - Run 19 - 12 inch Column
2 inch Tri-Packs

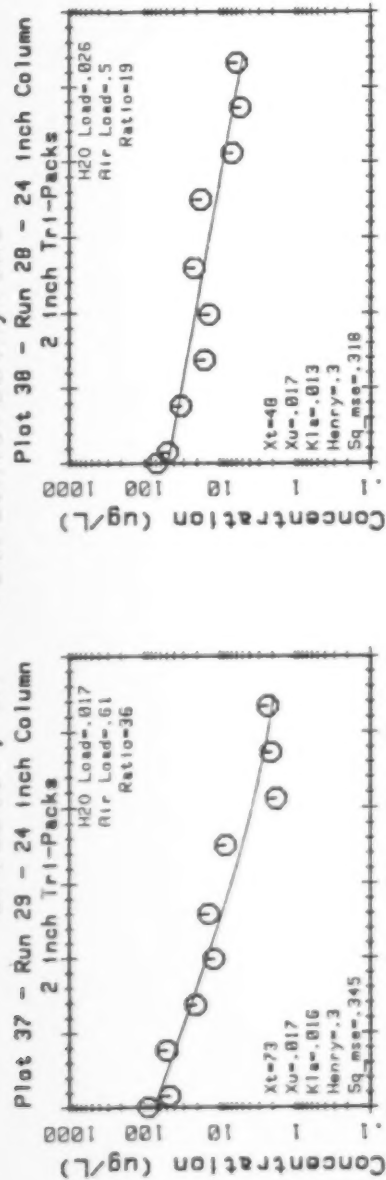


Location (Z) from Top of Packing (m)

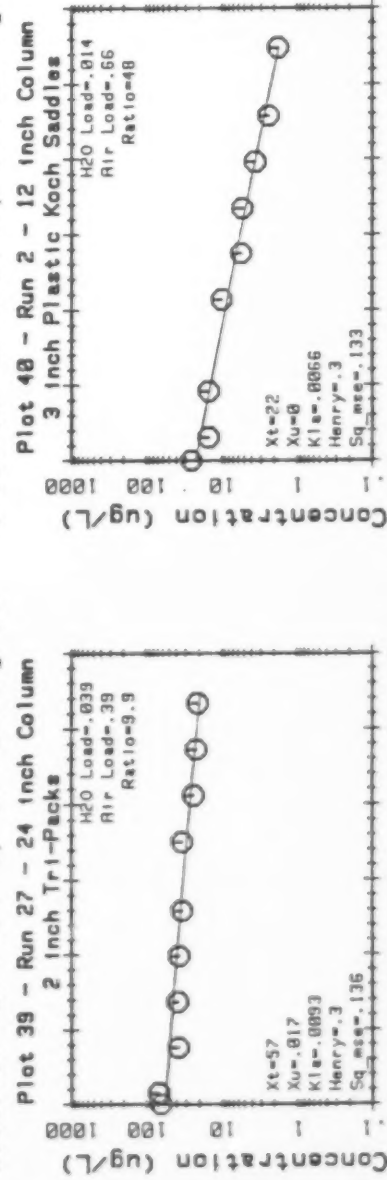
Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene



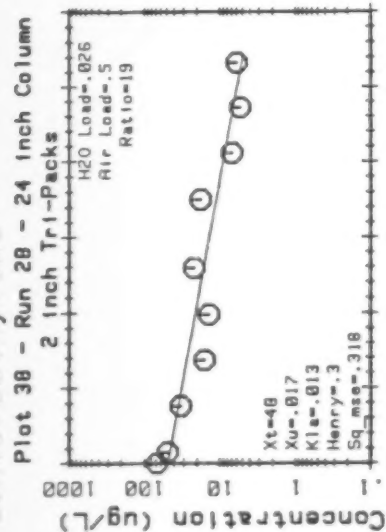
Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene



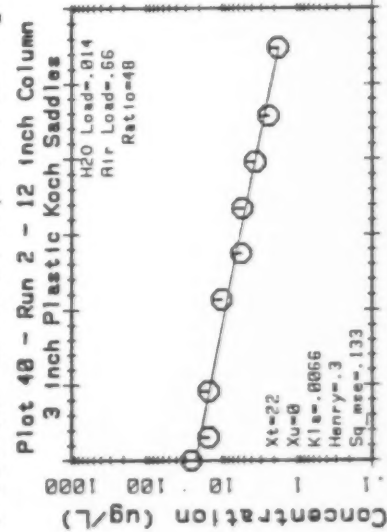
Location (Z) from Top of Packing (m)



Location (Z) from Top of Packing (m)



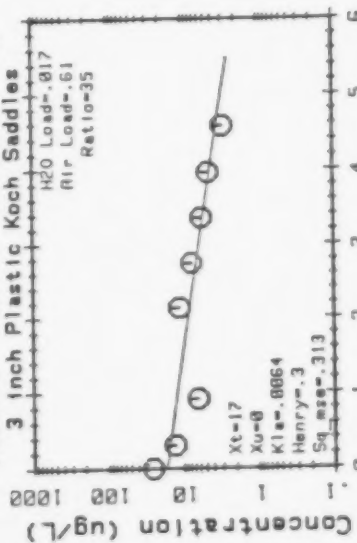
Location (Z) from Top of Packing (m)



Location (Z) from Top of Packing (m)

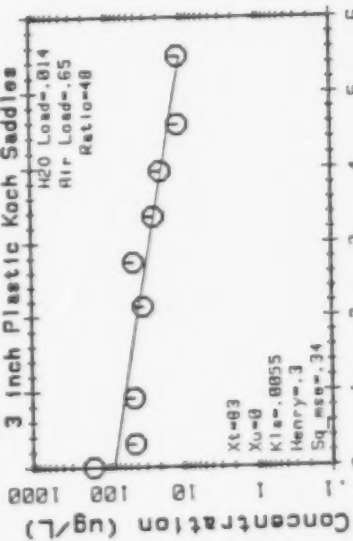
Packed Column Air Stripping Data
Brewster, NY - Tetrachloroethylene

Plot 41 - Run 4 - 12 Inch Column
3 inch Plastic Koch Saddles



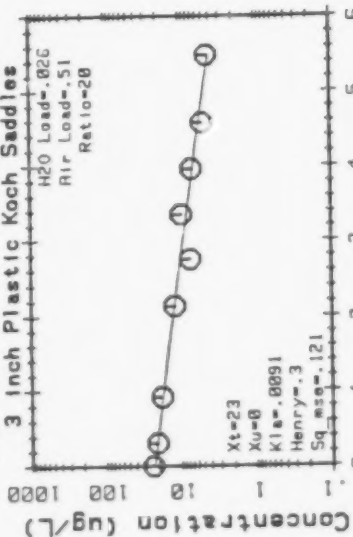
Location (Z) from Top of Packing (m)

Plot 43 - Run 15 - 12 Inch Column
3 inch Plastic Koch Saddles



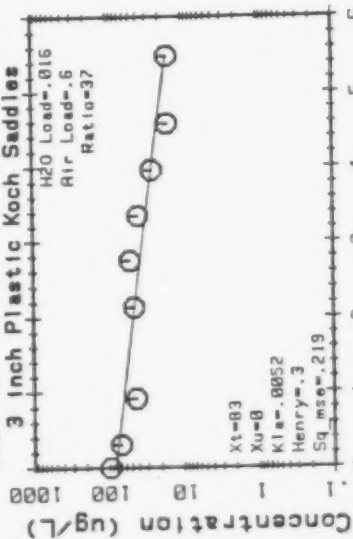
Location (Z) from Top of Packing (m)

Plot 42 - Run 5 - 12 Inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

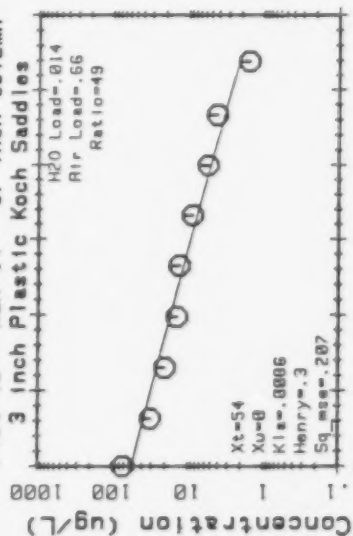
Plot 44 - Run 16 - 12 Inch Column
3 inch Plastic Koch Saddles



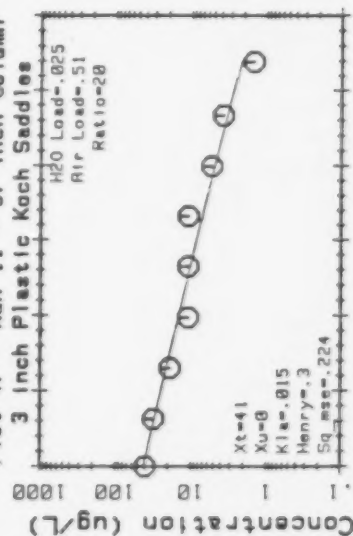
Location (Z) from Top of Packing (m)

Packed Column Air Stripping Data Brewster, NY - Tetrachloroethylene

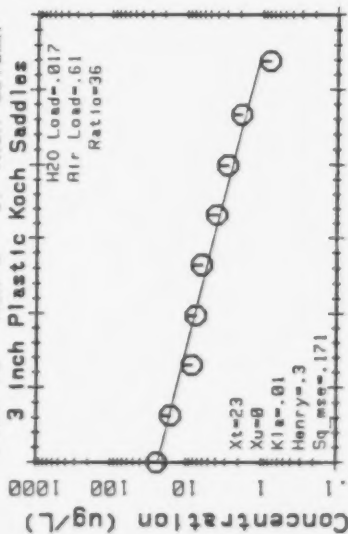
Plot 45 - Run 14 - 57 Inch Column
3 Inch Plastic Koch Saddles



Plot 47 - Run 11 - 57 Inch Column
3 Inch Plastic Koch Saddles



Plot 46 - Run 3 - 57 Inch Column
3 Inch Plastic Koch Saddles

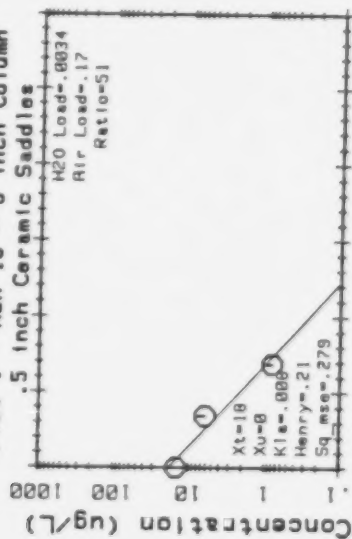


APPENDIX C

CONCENTRATION PROFILES FOR TRICHLOROETHYLENE

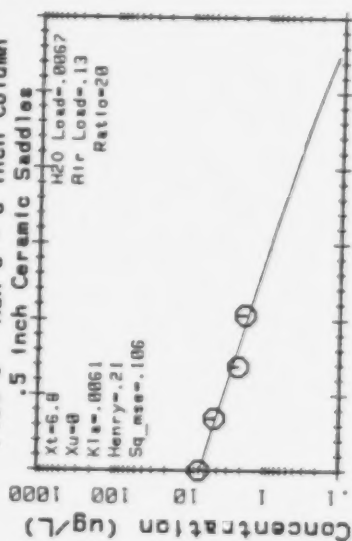
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 1 - Run 13 - 6 inch Column
.5 inch Ceramic Saddles



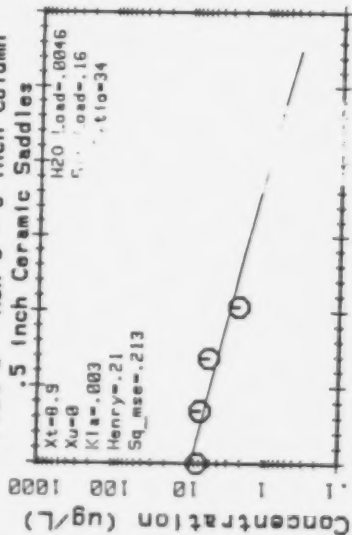
Location (Z) from Top of Packing (m)

Plot 3 - Run 8 - 6 inch Column
.5 inch Ceramic Saddles



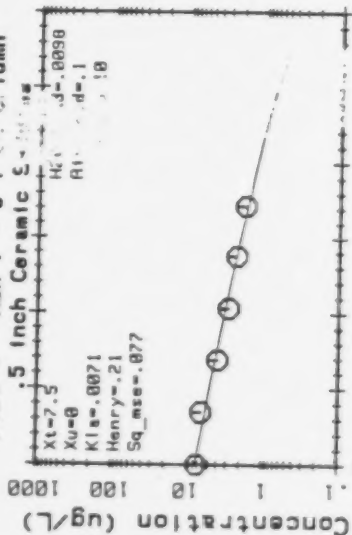
Location (Z) from Top of Packing (m)

Plot 2 - Run 9 - 6 inch Column
.5 inch Ceramic Saddles



Location (Z) from Top of Packing (m)

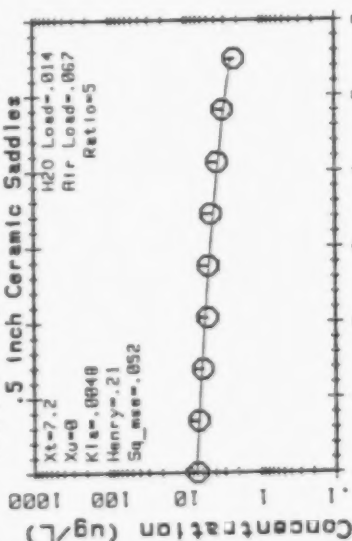
Plot 4 - Run 7 - 6 inch Column
.5 inch Ceramic Saddles



Location (Z) from Top of Packing (m)

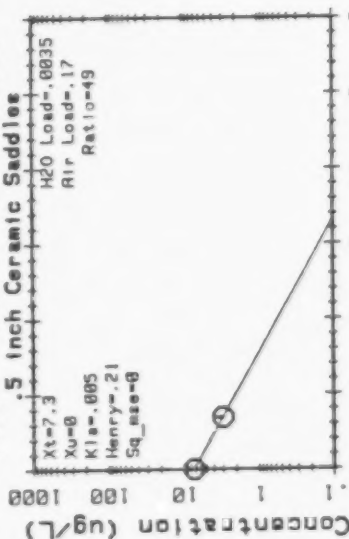
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 5 - Run 6 - 6 inch Column
.5 inch Ceramic Saddles



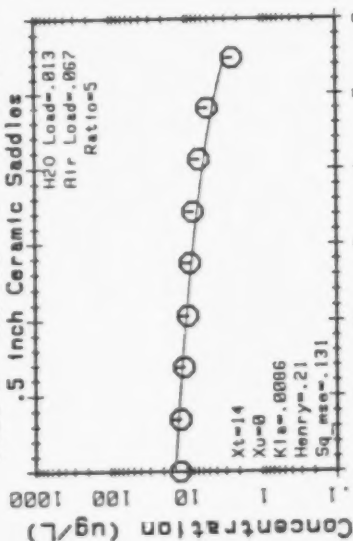
Location (Z) from Top of Packing (m)

Plot 7 - Run 18 - 6 inch Column
.5 inch Ceramic Saddles



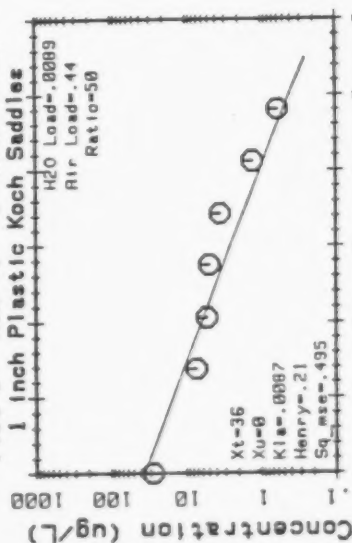
Location (Z) from Top of Packing (m)

Plot 6 - Run 12 - 6 inch Column
.5 inch Ceramic Saddles



Location (Z) from Top of Packing (m)

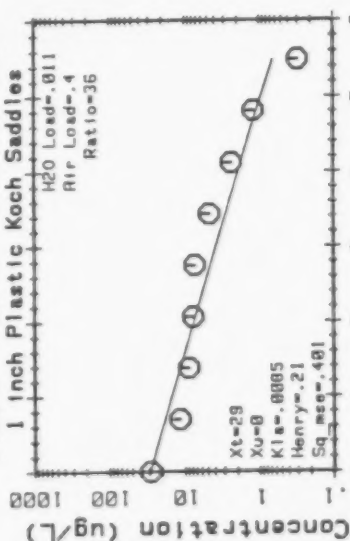
Plot 8 - Run 46 - 6 inch Column
1 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

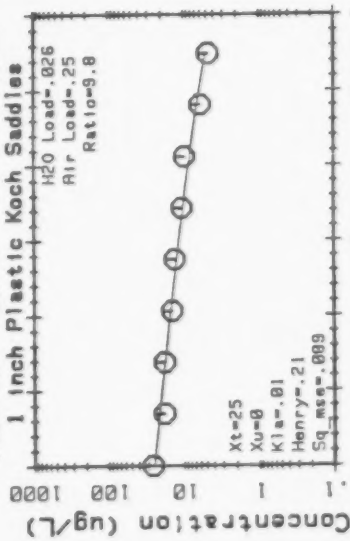
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 9 - Run 45 - 6 Inch Column
1 Inch Plastic Koch Saddles



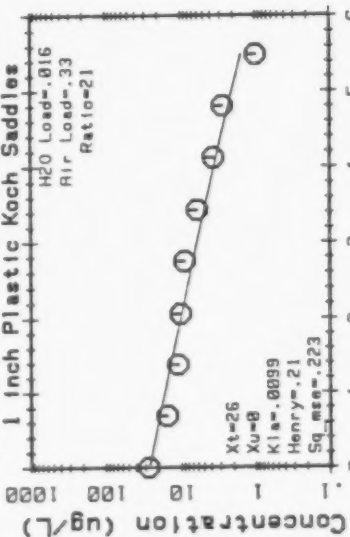
Location (Z) from Top of Packing (m)

Plot 11 - Run 48 - 6 Inch Column
1 Inch Plastic Koch Saddles



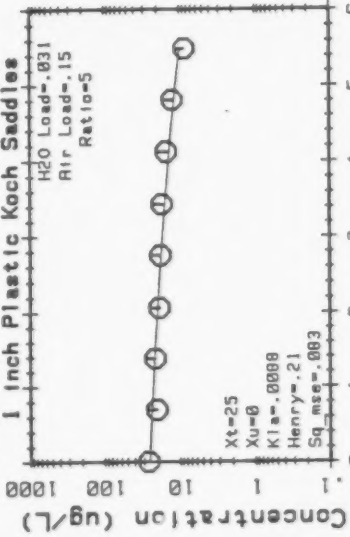
Location (Z) from Top of Packing (m)

Plot 10 - Run 44 - 6 Inch Column
1 Inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

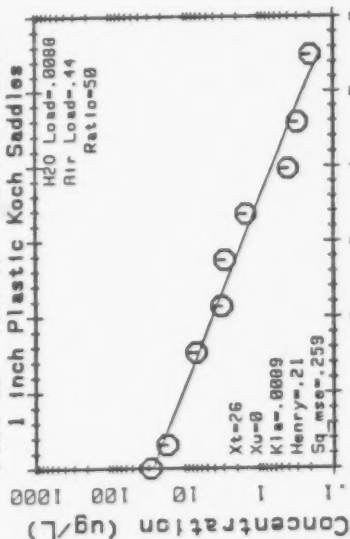
Plot 12 - Run 47 - 6 Inch Column
1 Inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

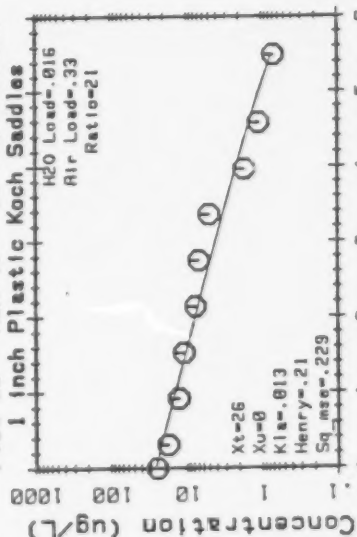
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 13 - Run 43 - 12 inch Column
1 inch Plastic Koch Saddles



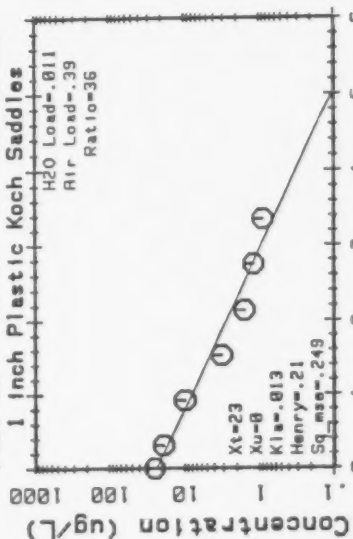
Location (Z) from Top of Packing (m)

Plot 15 - Run 41 - 12 inch Column
1 inch Plastic Koch Saddles



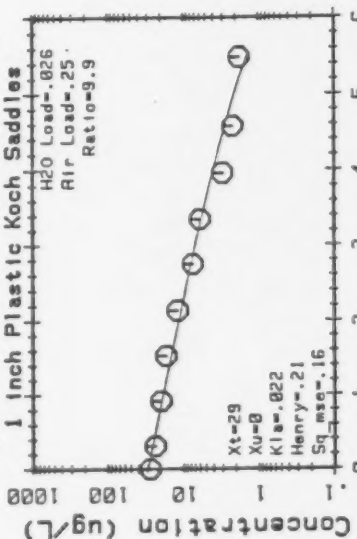
Location (Z) from Top of Packing (m)

Plot 14 - Run 42 - 12 inch Column
1 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

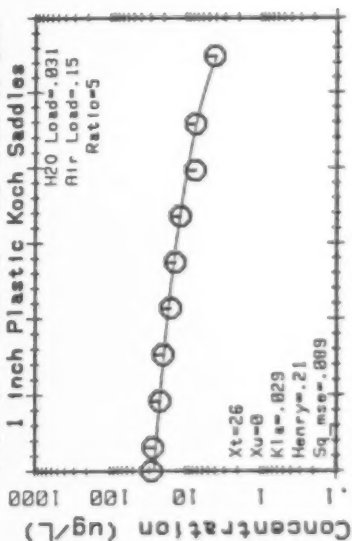
Plot 16 - Run 40 - 12 inch Column
1 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

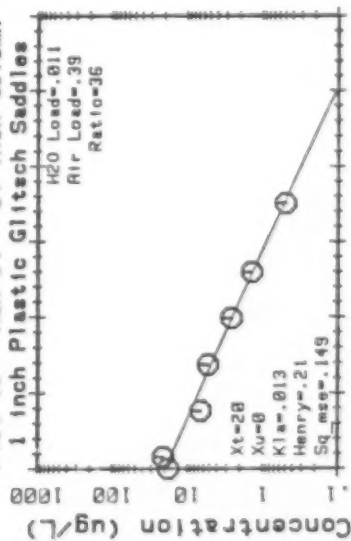
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 17 - Run 39 - 12 inch Column
1 inch Plastic Koch Saddles



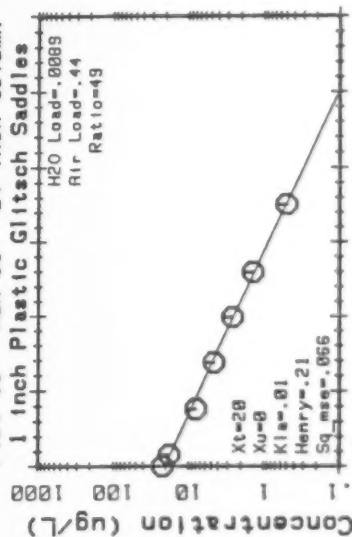
Location (Z) from Top of Packing (m)

Plot 19 - Run 34 - 24 inch Column
1 inch Plastic Glitsch Saddles



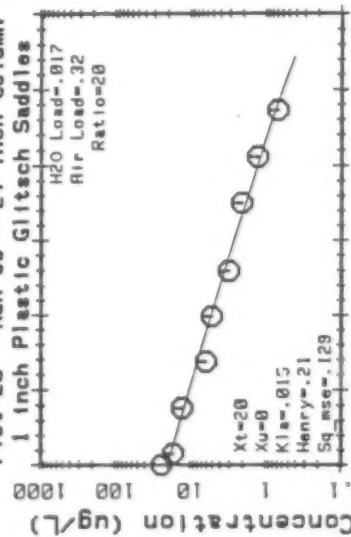
Location (Z) from Top of Packing (m)

Plot 18 - Run 35 - 24 inch Column
1 inch Plastic Glitsch Saddles



Location (Z) from Top of Packing (m)

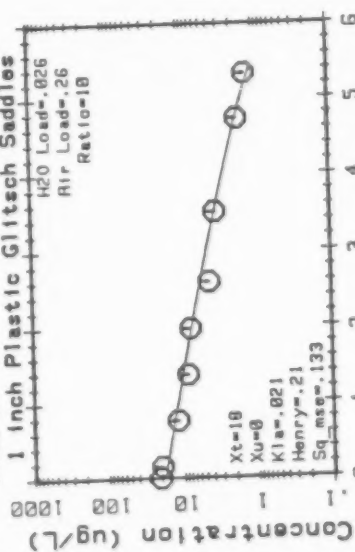
Plot 20 - Run 33 - 24 inch Column
1 inch Plastic Glitsch Saddles



Location (Z) from Top of Packing (m)

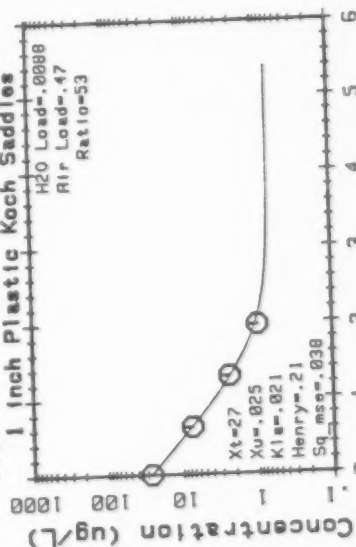
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 21 - Run 32 - 24 inch Column
1 inch Plastic Glitsch Saddles



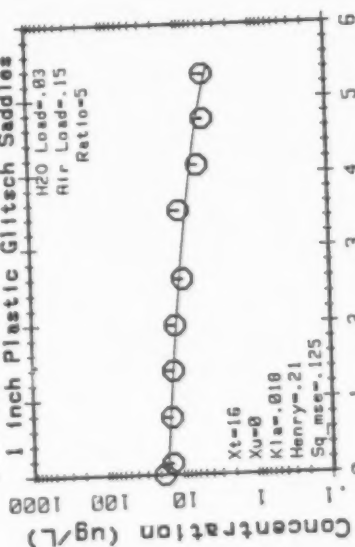
Location (Z) from Top of Packing (m)

Plot 23 - Run 38 - 57 inch Column
1 inch Plastic Koch Saddles



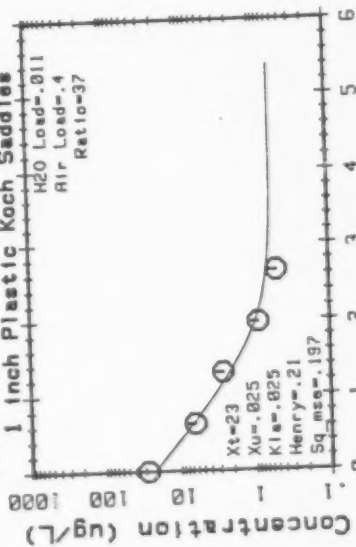
Location (Z) from Top of Packing (m)

Plot 22 - Run 31 - 24 inch Column
1 inch Plastic Glitsch Saddles



Location (Z) from Top of Packing (m)

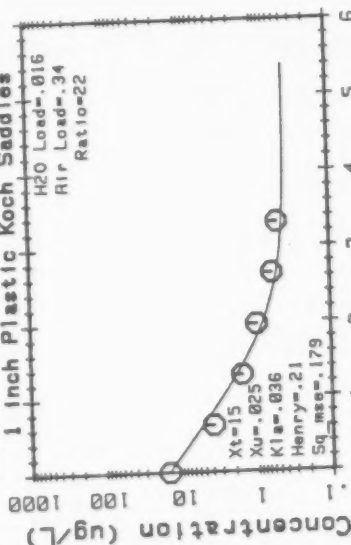
Plot 24 - Run 37 - 57 inch Column
1 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

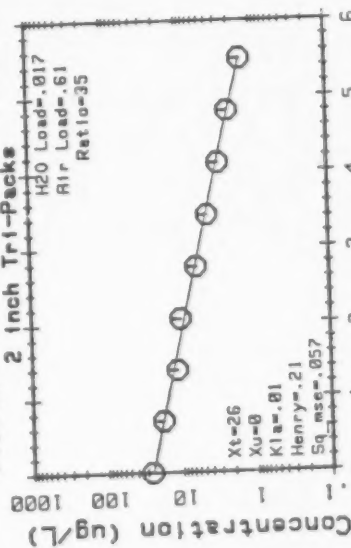
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 25 - Run 36 - 57 inch Column
1 inch Plastic Koch Saddles



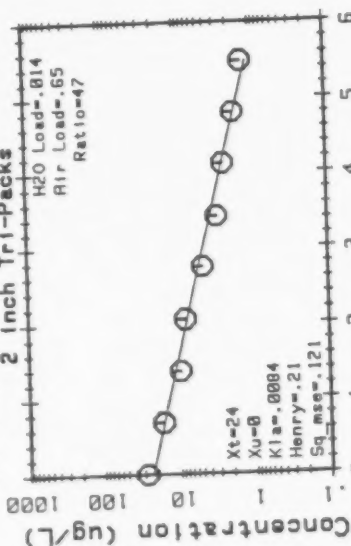
Location (Z) from Top of Packing (m)

Plot 27 - Run 28 - 6 inch Column
2 inch Tri-Packs



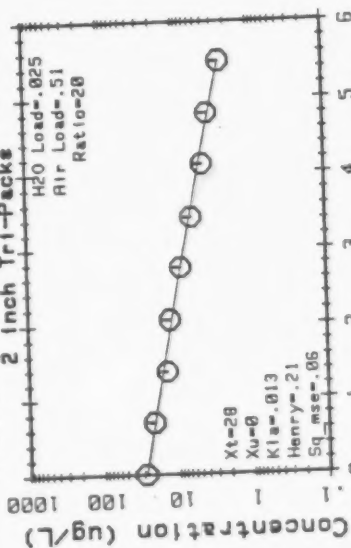
Location (Z) from Top of Packing (m)

Plot 26 - Run 18 - 6 inch Column
2 inch Tri-Packs



Location (Z) from Top of Packing (m)

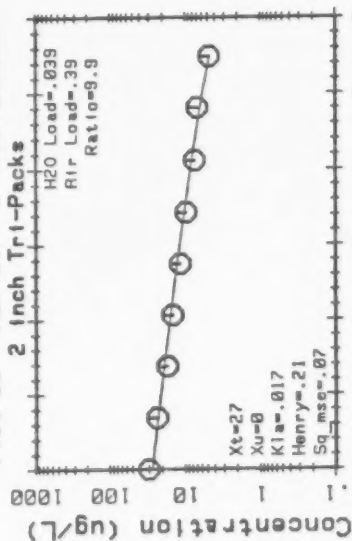
Plot 28 - Run 22 - 6 inch Column
2 inch Tri-Packs



Location (Z) from Top of Packing (m)

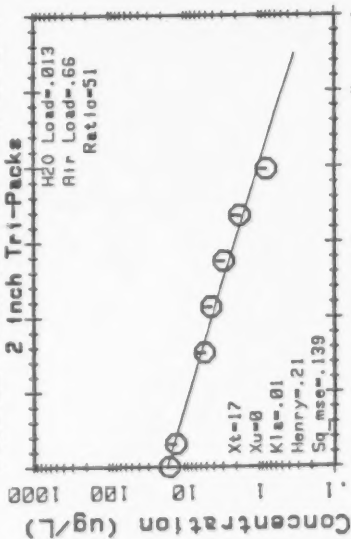
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 29 - Run 24 - 6 inch Column



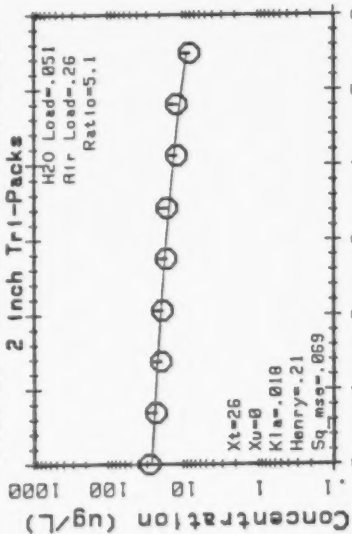
Location (Z) from Top of Packing (m)

Plot 31 - Run 17 - 12 inch Column



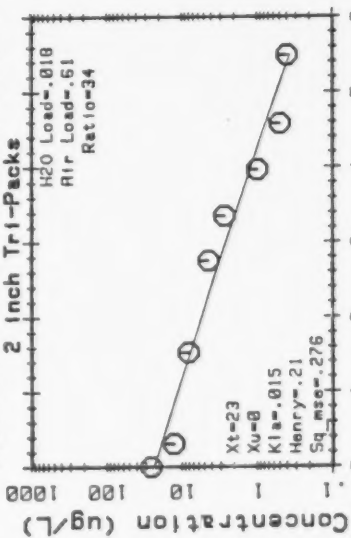
Location (Z) from Top of Packing (m)

Plot 30 - Run 26 - 6 inch Column



Location (Z) from Top of Packing (m)

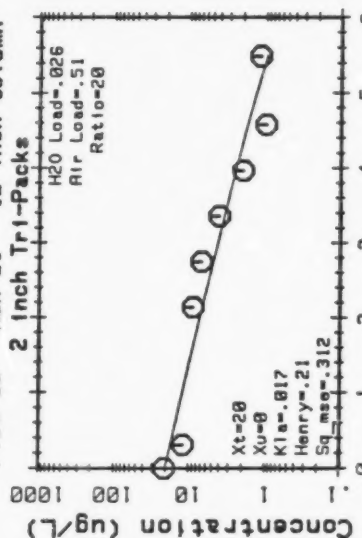
Plot 32 - Run 19 - 12 inch Column



Location (Z) from Top of Packing (m)

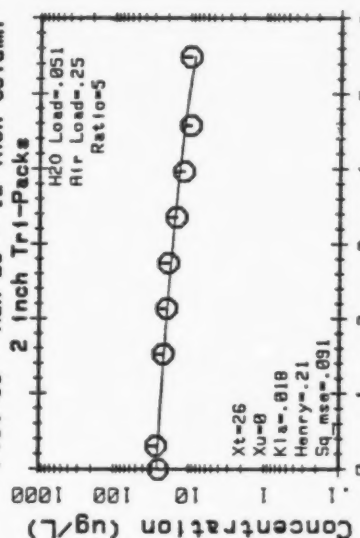
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 33 - Run 21 - 12 Inch Column
2 Inch Tri-Packs



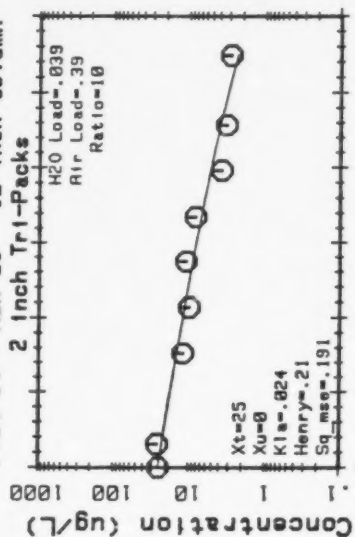
Location (Z) from Top of Packing (m)

Plot 35 - Run 25 - 12 Inch Column
2 Inch Tri-Packs



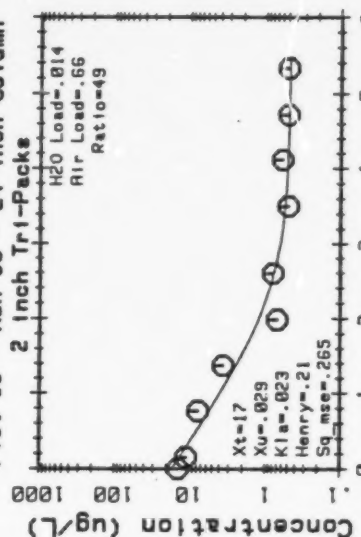
Location (Z) from Top of Packing (m)

Plot 34 - Run 23 - 12 Inch Column
2 Inch Tri-Packs



Location (Z) from Top of Packing (m)

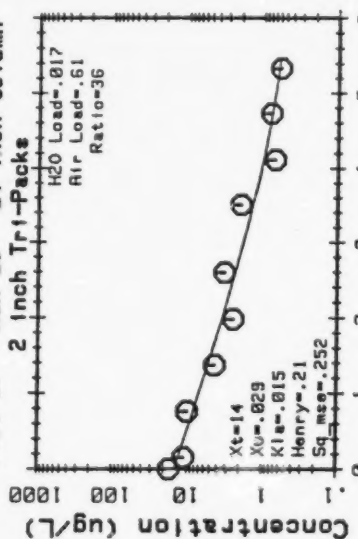
Plot 36 - Run 38 - 24 Inch Column
2 Inch Tri-Packs



Location (Z) from Top of Packing (m)

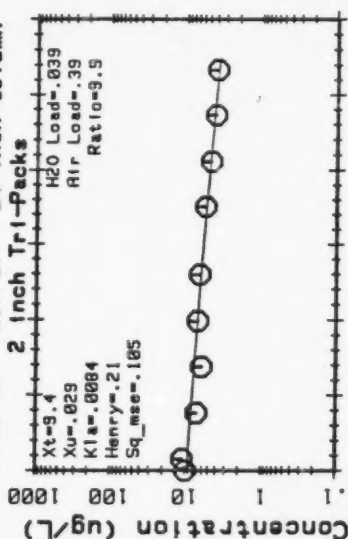
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 37 - Run 29 - 24 inch Column
2 inch Tri-Packs



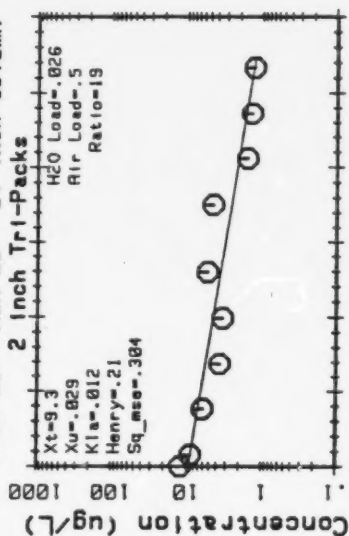
Location (Z) from Top of Packing (m)

Plot 39 - Run 27 - 24 inch Column
2 inch Tri-Packs



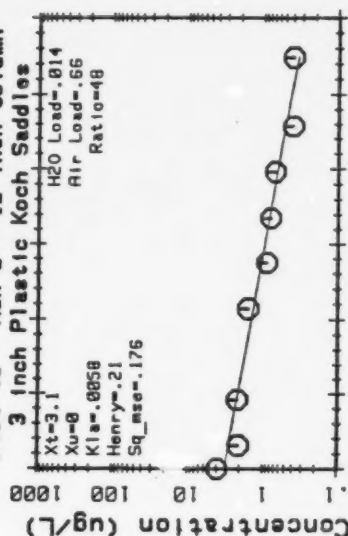
Location (Z) from Top of Packing (m)

Plot 38 - Run 28 - 24 inch Column
2 inch Tri-Packs



Location (Z) from Top of Packing (m)

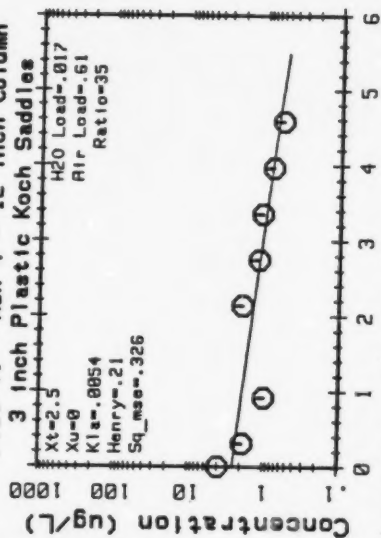
Plot 40 - Run 2 - 12 inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

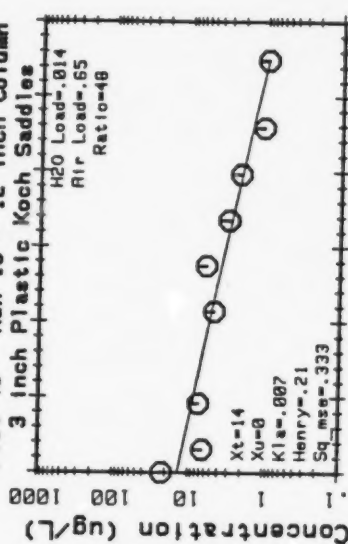
Packed Column Air Stripping Data
Brewster, NY - Trichloroethylene

Plot 41 - Run 4 - 12 inch Column
3 inch Plastic Koch Saddles



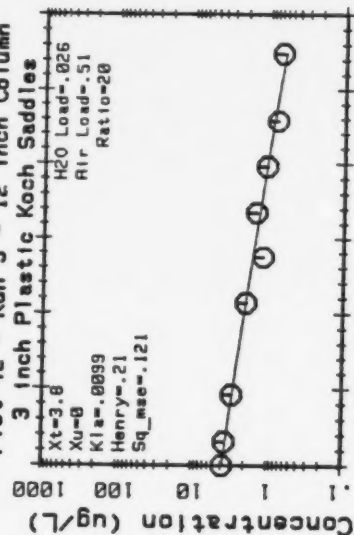
Location (Z) from Top of Packing (m)

Plot 43 - Run 15 - 12 inch Column
3 inch Plastic Koch Saddles



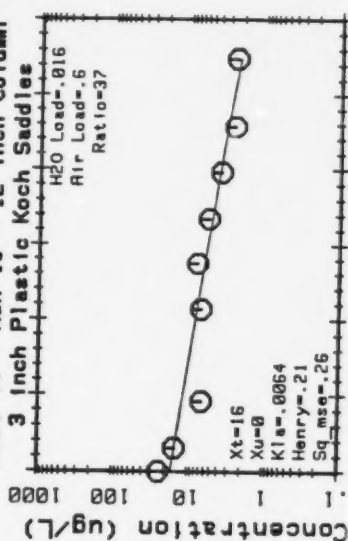
Location (Z) from Top of Packing (m)

Plot 42 - Run 5 - 12 inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

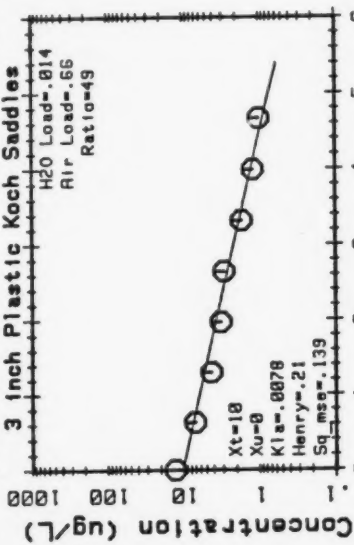
Plot 44 - Run 16 - 12 inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

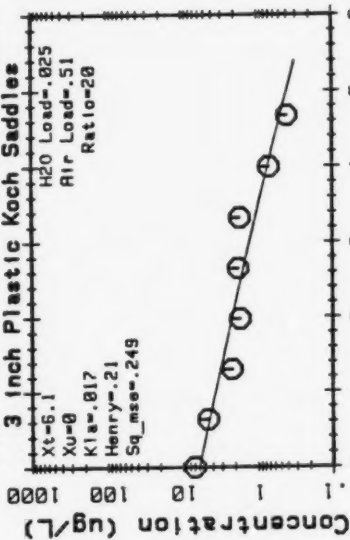
Packed Column Air Stripping Data Brewster, NY - Trichloroethylene

Plot 45 - Run 14 - 57 inch Column
3 inch Plastic Koch Saddles



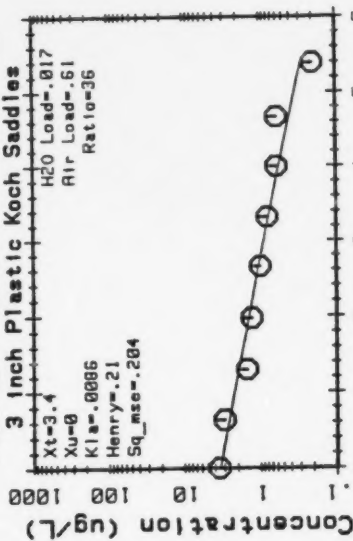
Location (Z) from Top of Packing (m)

Plot 47 - Run 11 - 57 inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

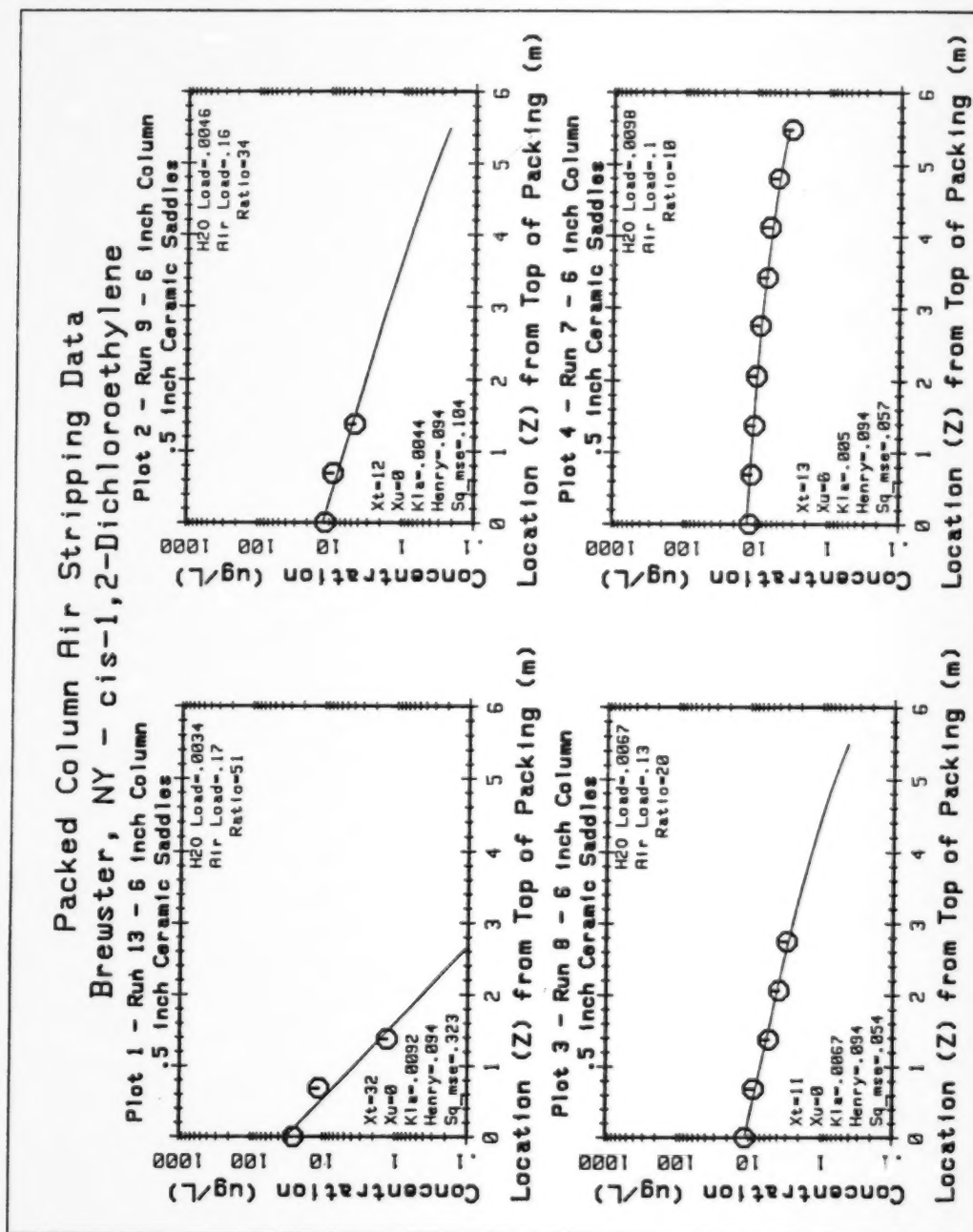
Plot 46 - Run 3 - 57 inch Column
3 inch Plastic Koch Saddles



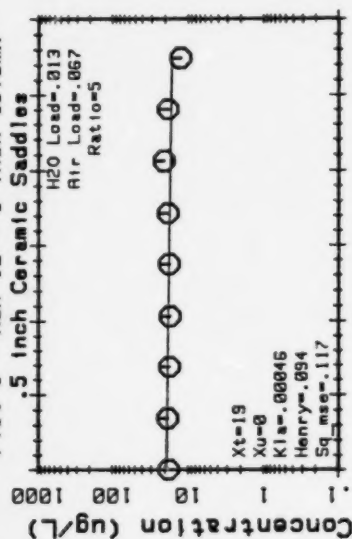
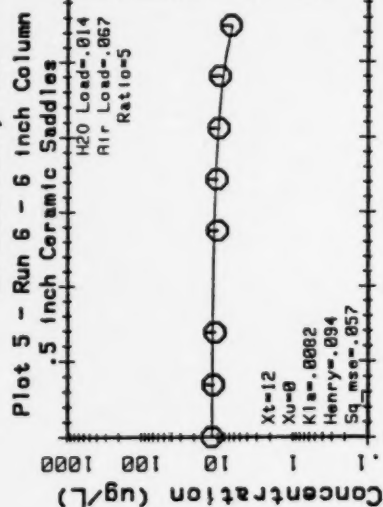
Location (Z) from Top of Packing (m)

APPENDIX D

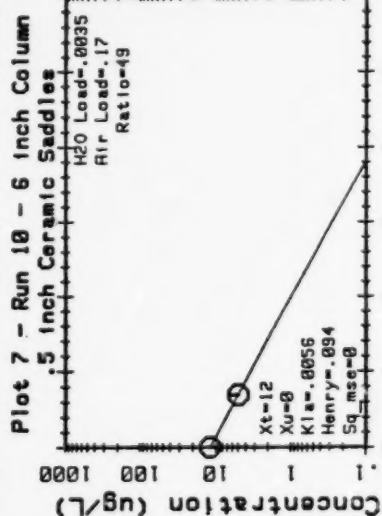
CONCENTRATION PROFILES FOR CIS-1,2 DICHLOROETHYLENE



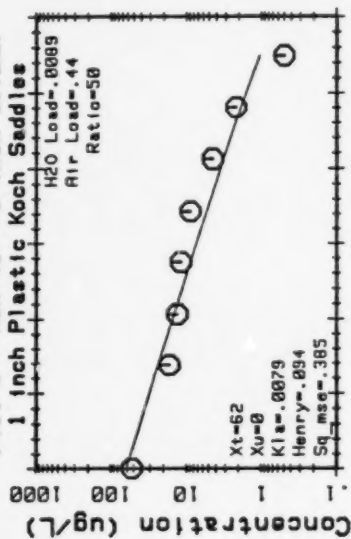
Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene



Location (Z) from Top of Packing (m)



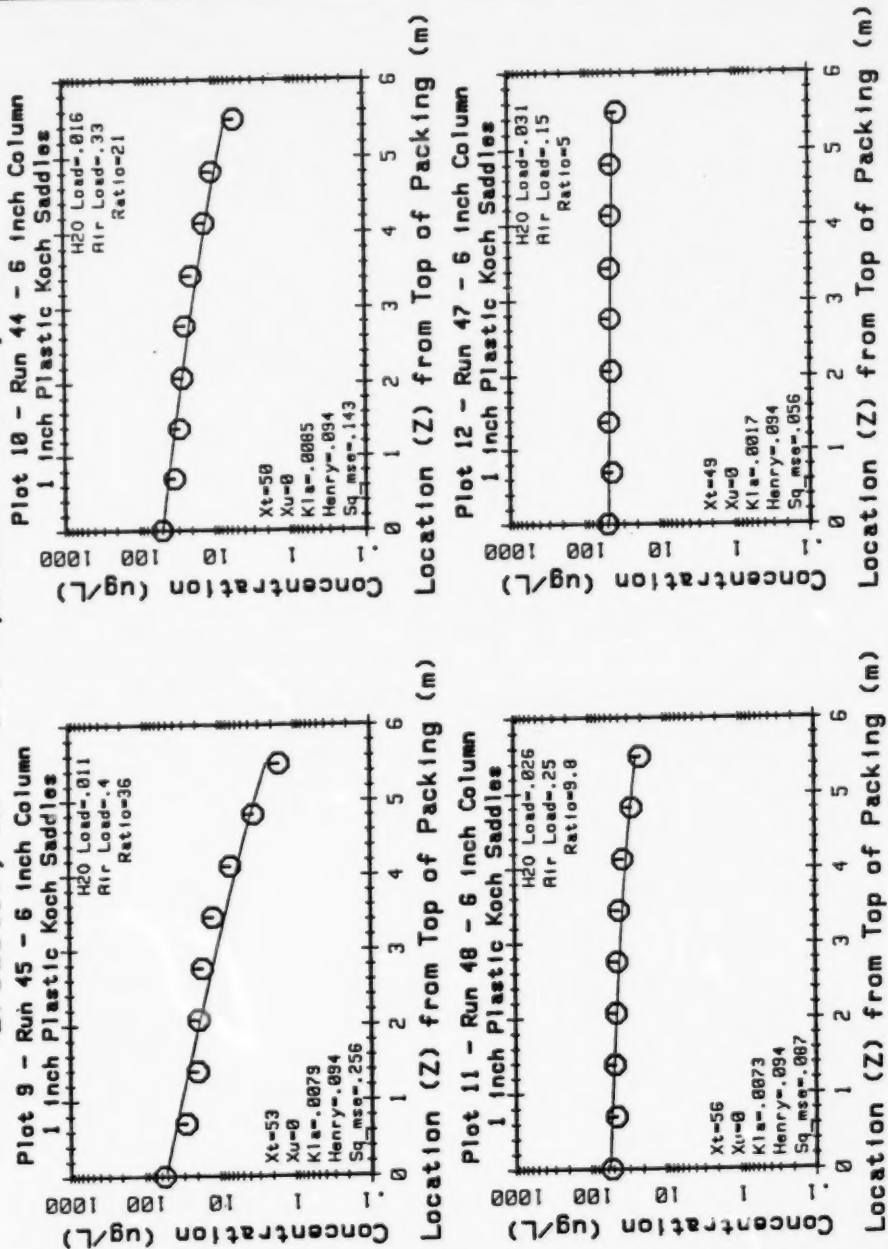
Location (Z) from Top of Packing (m)



Location (Z) from Top of Packing (m)

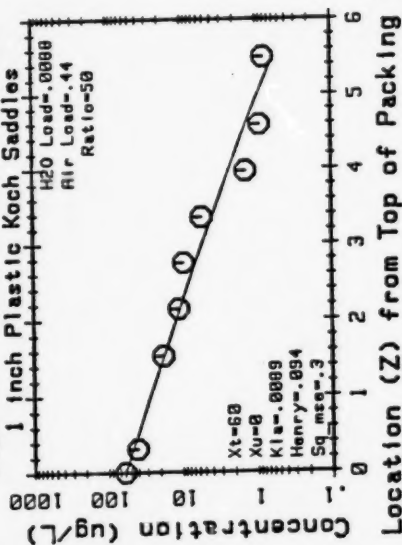
Location (Z) from Top of Packing (m)

Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene

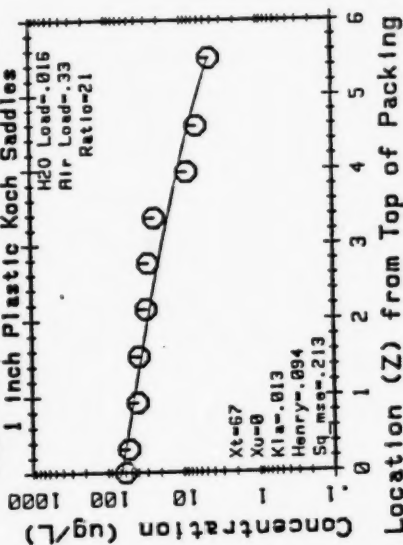


Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene

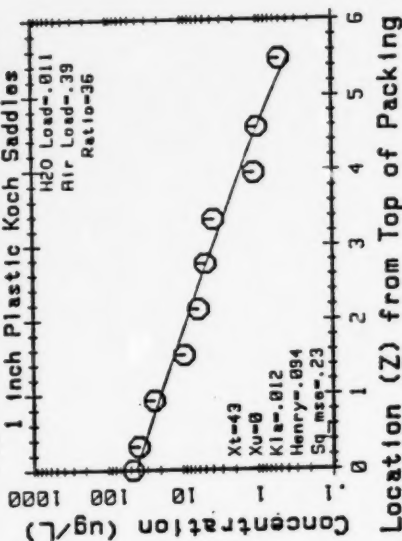
Plot 13 - Run 43 - 12 inch Column
1 inch Plastic Koch Saddles



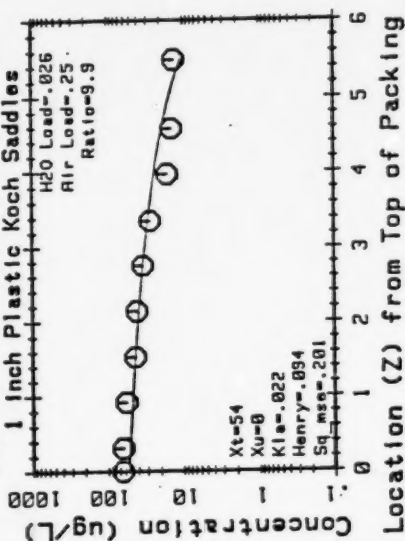
Plot 15 - Run 41 - 12 inch Column
1 inch Plastic Koch Saddles



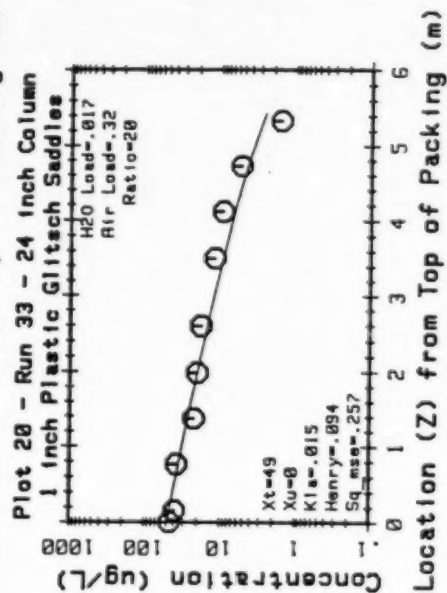
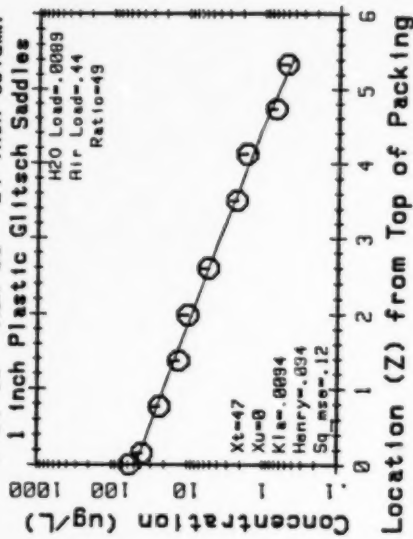
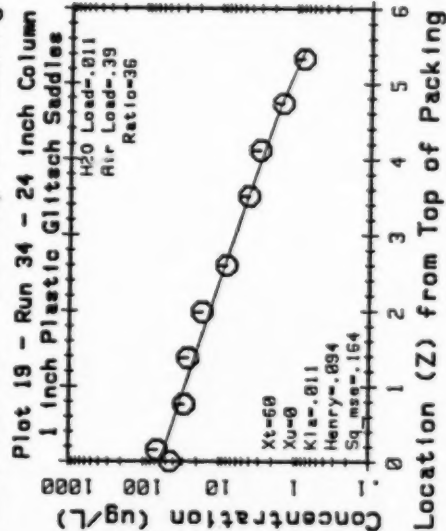
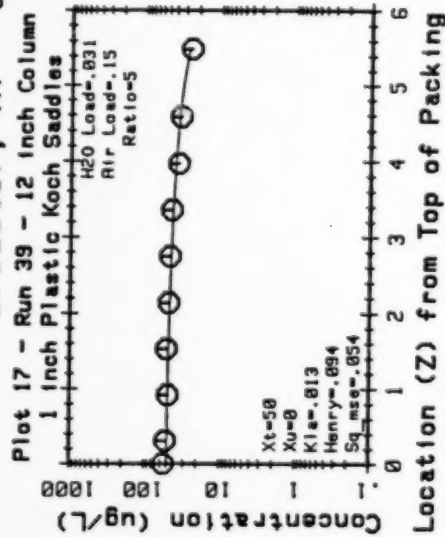
Plot 14 - Run 42 - 12 inch Column
1 inch Plastic Koch Saddles



Plot 16 - Run 40 - 12 inch Column
1 inch Plastic Koch Saddles



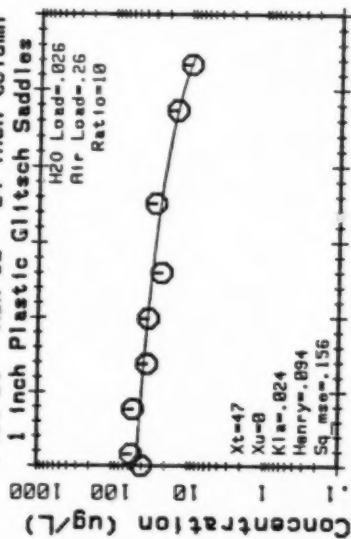
Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene



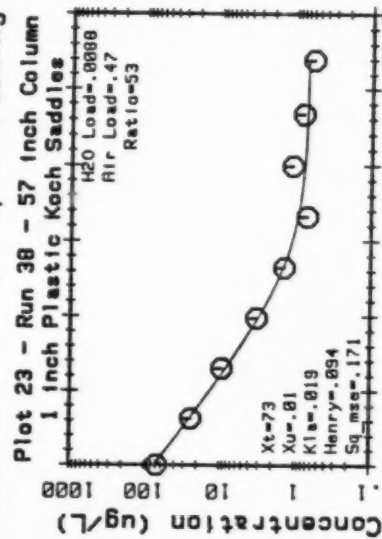
Packed Column Air Stripping Data

Brewster, NY - cis-1,2-Dichloroethylene

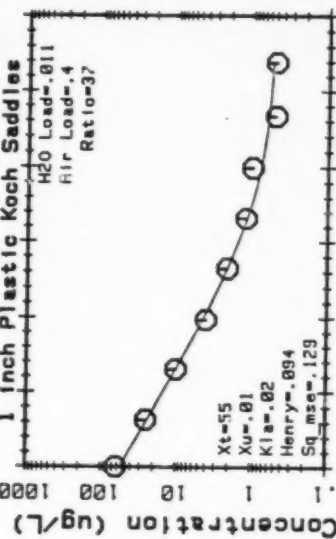
Plot 21 - Run 32 - 24 inch Column



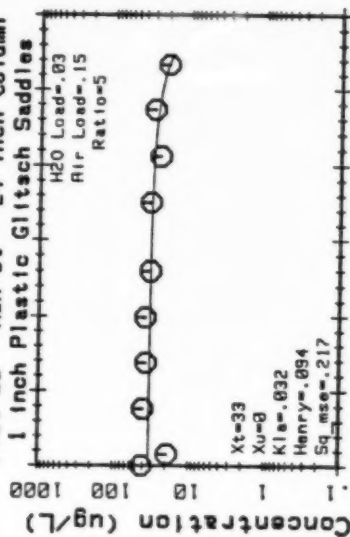
Plot 23 - Run 38 - 57 inch Column



Plot 24 - Run 37 - 57 inch Column



Plot 22 - Run 31 - 24 inch Column

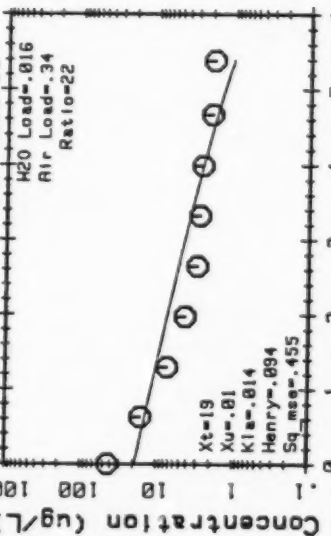


Packed Column Air Stripping Data

Brewster, NY - cis-1,2-Dichloroethylene

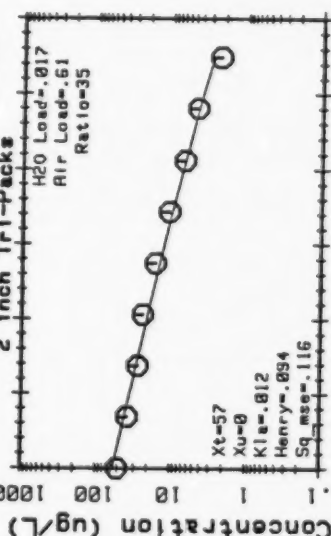
Plot 25 - Run 36 - 57 inch Column

1 inch Plastic Koch Saddles



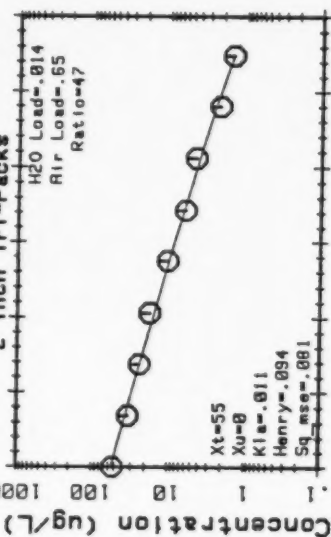
Plot 27 - Run 20 - 6 inch Column

2 inch Tri-Packs



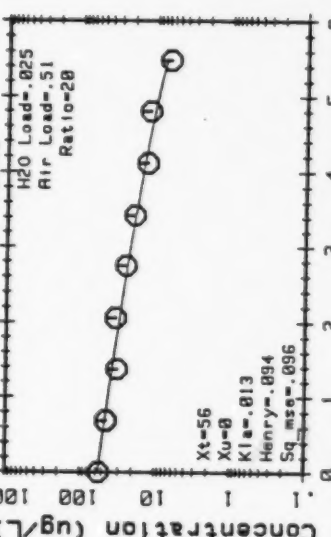
Plot 26 - Run 18 - 6 inch Column

2 inch Tri-Packs



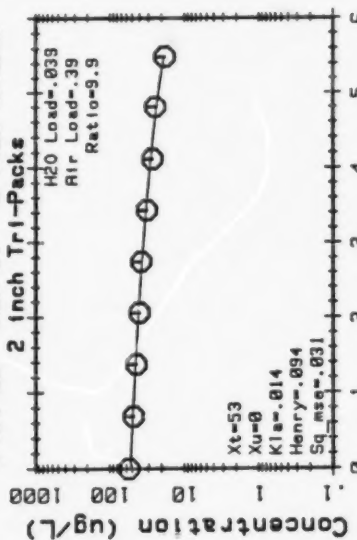
Plot 28 - Run 22 - 6 inch Column

2 inch Tri-Packs



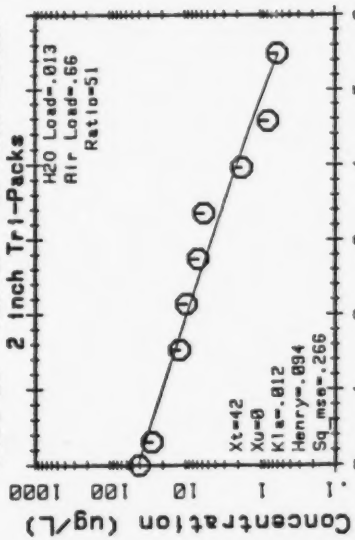
Packed Column Air Stripping Data
Brewster, NY - cis-1,2-Dichloroethylene

Plot 29 - Run 24 - 6 inch Column
2 inch Tri-Packs



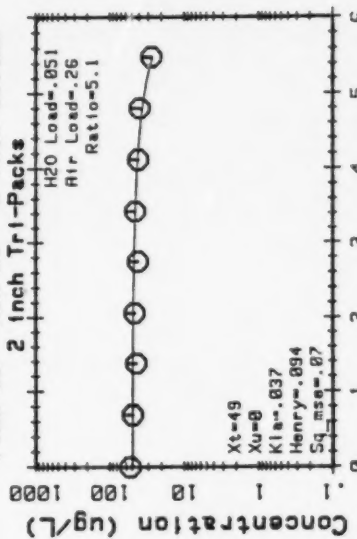
Location (Z) from Top of Packing (m)

Plot 31 - Run 17 - 12 inch Column
2 inch Tri-Packs



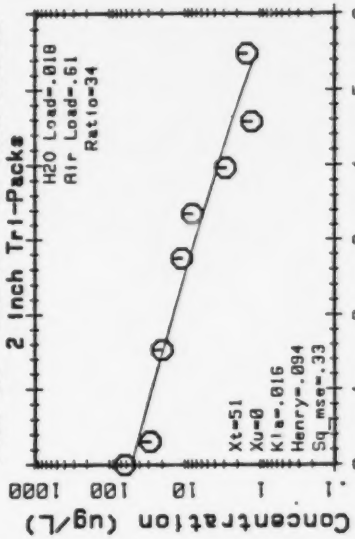
Location (Z) from Top of Packing (m)

Plot 30 - Run 26 - 6 inch Column
2 inch Tri-Packs



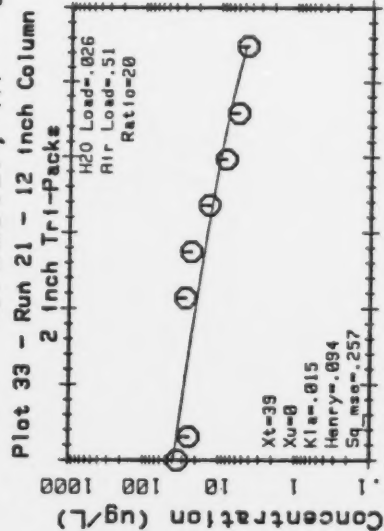
Location (Z) from Top of Packing (m)

Plot 32 - Run 19 - 12 inch Column
2 inch Tri-Packs

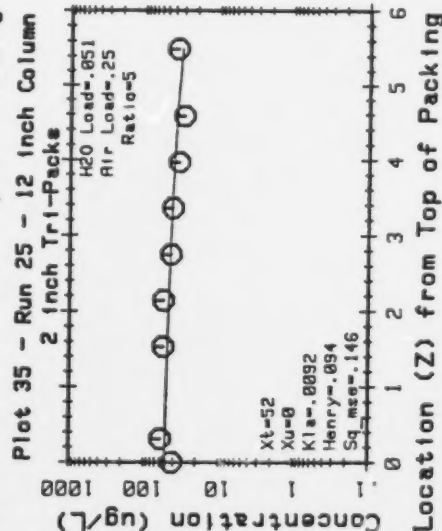


Location (Z) from Top of Packing (m)

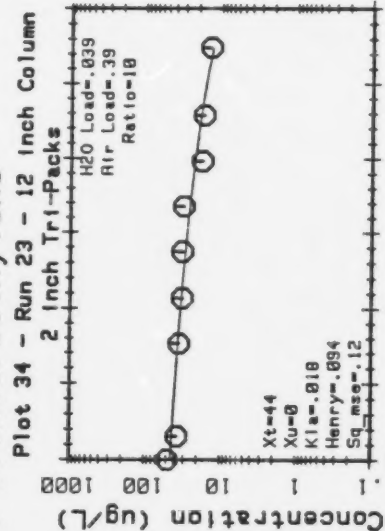
Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene



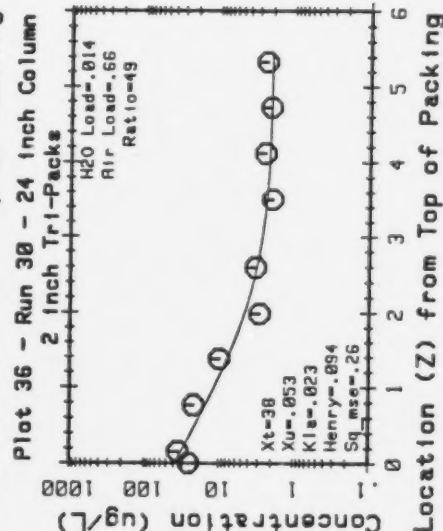
Location (Z) from Top of Packing (m)



Location (Z) from Top of Packing (m)

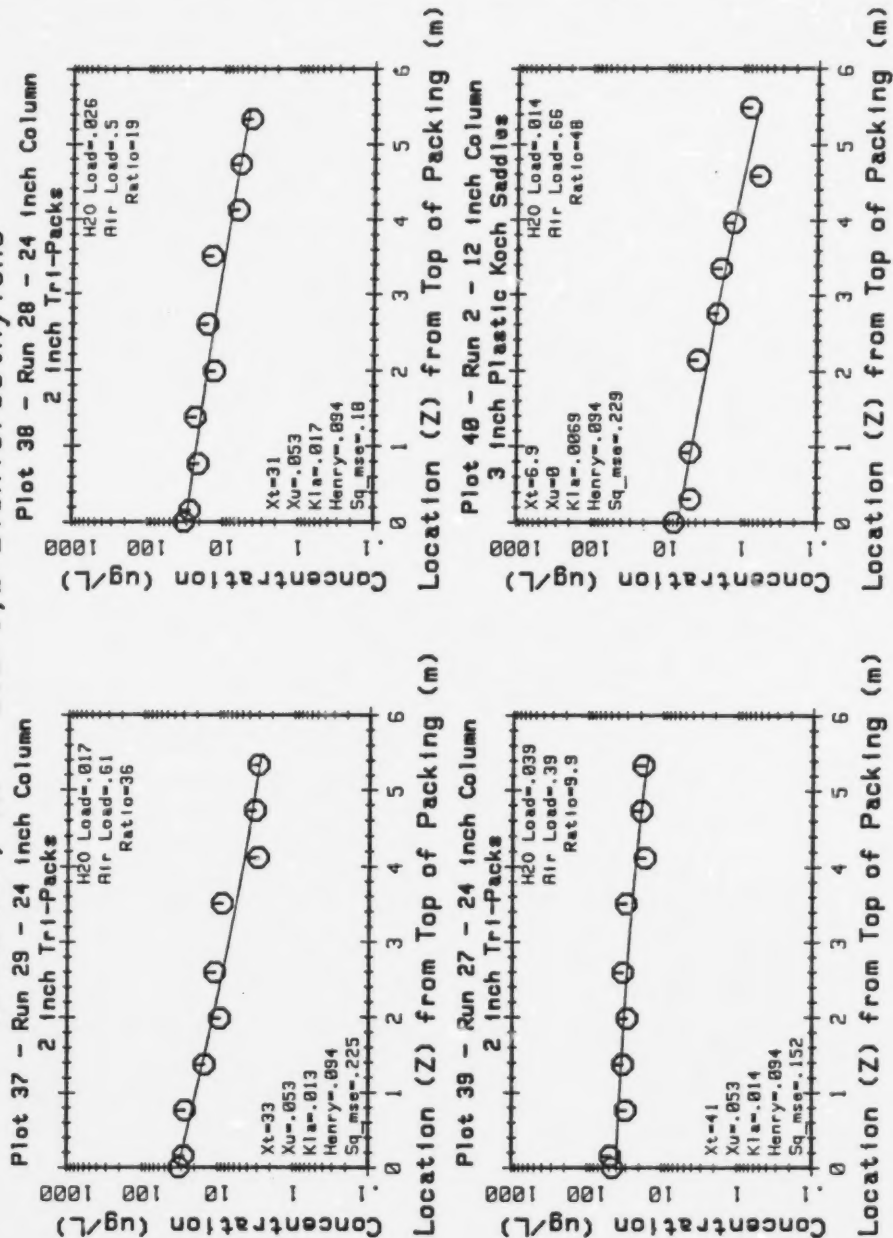


Location (Z) from Top of Packing (m)



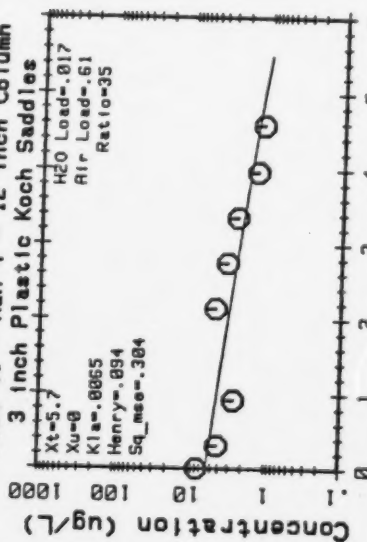
Location (Z) from Top of Packing (m)

Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene

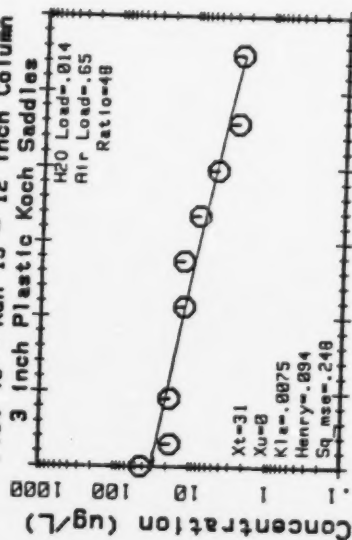


Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene

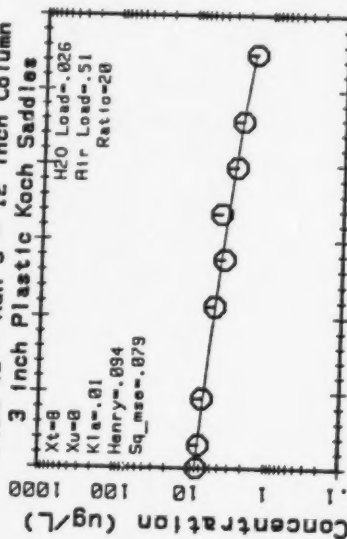
Plot 41 - Run 4 - 12 inch Column
3 inch Plastic Koch Saddles



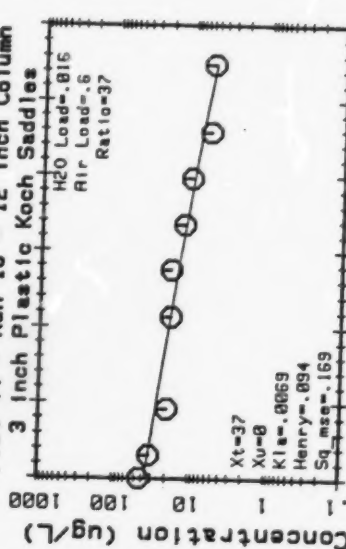
Plot 43 - Run 15 - 12 inch Column
3 inch Plastic Koch Saddles



Plot 42 - Run 5 - 12 inch Column
3 inch Plastic Koch Saddles

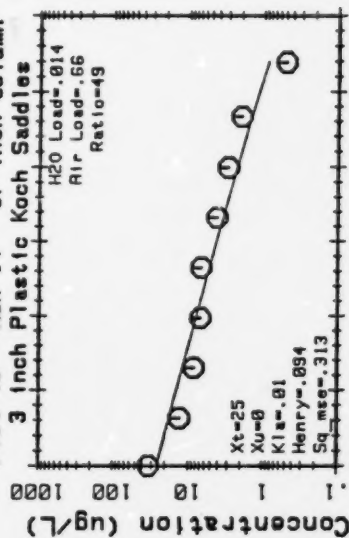


Plot 44 - Run 16 - 12 inch Column
3 inch Plastic Koch Saddles



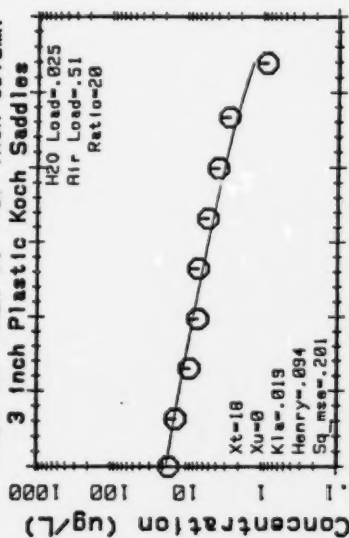
Packed Column Air Stripping Data Brewster, NY - cis-1,2-Dichloroethylene

Plot 45 - Run 14 - 57 inch Column
3 inch Plastic Koch Saddles



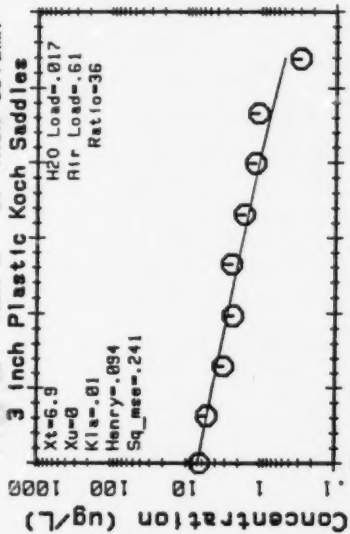
Location (Z) from Top of Packing (m)

Plot 47 - Run 11 - 57 inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

Plot 46 - Run 3 - 57 inch Column
3 inch Plastic Koch Saddles



Location (Z) from Top of Packing (m)

APPENDIX E

BLOWER POWER MEASUREMENTS

TABLE E-1. POWER DATA - 6" COLUMN

<u>Run No.</u>	<u>Amps</u>	<u>Volts</u>	<u>Power (kw)</u>	<u>Packing Type</u>
6	1.8	236	0.42	1/2" saddles
12	1.8	238	0.43	1/2" saddles
7	1.7	237	0.40	1/2" saddles
8	1.7	237	0.40	1/2" saddles
9	1.7	236	0.40	1/2" saddles
10	1.7	237	0.40	1/2" saddles
13	1.8	238	0.43	1/2" saddles
26	2.0	210	0.42	2" TRI-PACKS
24	1.9	215	0.41	2" TRI-PACKS
22	1.7	260	0.44	2" TRI-PACKS
20	1.7	260	0.44	2" TRI-PACKS
18	1.7	259	0.44	2" TRI-PACKS

TABLE E-2. POWER DATA - 12" COLUMN

<u>Run No.</u>	<u>Amps</u>	<u>Volts</u>	<u>Power (kw)</u>	<u>Packing Type</u>
5	7.8	118	0.92	3" saddles
4	8.0	118	0.94	3" saddles
16	8.7	-	-	3" saddles
2	7.9	118	0.93	3" saddles
15	7.4	119	0.88	3" saddles
25	-	-	-	2" TRI-PACKS
23	8.0	131	1.00	2" TRI-PACKS
21	7.7	129	0.99	2" TRI-PACKS
19	6.7	130	0.87	2" TRI-PACKS
17	8.4	130	1.09	2" TRI-PACKS

TABLE E-3. POWER DATA - 57" COLUMN

<u>Run No.</u>	<u>Amps</u>	<u>Volts</u>	<u>Power (kw)</u> (a)	<u>Packing Type</u>
11	13.9	230	5.53	3" Saddles
3	14.5	236	5.92	3" Saddles
1	15.2	232	6.10	3" Saddles
14	15.2	234	6.15	3" Saddles
36	12.0	255	5.3	1" Saddles
37	12.2	255	5.39	1" Saddles
38	13.0	255	5.74	1" Saddles

(a) Three phase power. Power = $\sqrt{3}$ x amps x volts

APPENDIX F
ENVIRONMENTAL CONDITIONS

TABLE F-1. ENVIRONMENTAL CONDITIONS

Date	Run Nos.	Wind Speed (mph)	Relative Humidity			General Weather
			Dry Bulb (° C)	Wet Bulb (° C)	RH (%)	
10/24/84	1 - 4	< 1	12.8	9.7	68	Cloudy
10/29/84	5	< 1	15.0	14.5	95	Cloudy
11/8/84	6-10	0-2	7.2	4.2	62	Sunny
11/19/84	11	0-2	3.5	1.0	62	Cloudy
12/4/84	12, 13	0-4	3.0	1.0	70	Mostly Sunny
12/14/84	14	0-1	3.2	1.2	70	Cloudy
1/3/85	15	2	3.0	0	54	Cloudy
1/9/85	16	2	-3	-6	35	Sunny
2/20/85	17-22	< 2	5	1	45	Mostly Sunny
2/20/85	23-26	< 2	7	2	38	Mostly Sunny
3/5/85	27-30	0-6	11.5	8.0	62	Partly Sunny
3/6/85	31-35	0-5	-1.8	-4.0	54	Sunny
4/11/85	36-38	2-8	11.0	6.7	54	Mostly Sunny
5/13/85	39-46	1-6	24.8	21.4	74	Mostly Sunny
5/14/85	47-48	< 1	23.0	16.5	52	Sunny